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MASTER'S THESIS

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Abstract

Equipment maintenance is an essential part of any industrial plant. While fundamental, evaluating its impact quantitatively is a great challenge. Companies usually find it hard to obtain reliable financial support figures to justify the replacement of ageing equipment. Gassco AS identified this matter and provided the basis for this master thesis. This work's objective is to provide a methodology that supports decision-making for maintenance management in a factual manner. Such feature was done after an exhaustive survey of current methods.

Equipment reliability is an essential part of determining potential losses. A system's losses due to unreliability depend on subcomponent interdependencies and individual failure rates. A model combining two existing ones was developed: EVA (Economic Value Added) and CoUr (Cost of Unreliability). A real case concerning the potential replacement of UPS (Uninterruptible Power Supply) units was used to test the suggested method. A tool based in a spreadsheet software was developed in able to easily use the recommended model for analysis purposes. The results obtained deemed such investment as non-justifiable financially. The proposed tool is a cornerstone towards better decision-making support. Nonetheless, it still has room for added robustness.

Acknowledgments

This written report is the result of both individual and collaborative efforts. I would like to start by expressing my gratitude towards the CONACYT (Consejo Nacional de Ciencia y Tecnología) in Mexico. Their financial aid was crucial in enabling me to complete a graduate degree at UiS.

I thank Stian Bjerkenes from Gassco AS for acting as my external supervisor throughout this process. I got constant and important support from both himself and his working peers. A special mention to Anders Thomassen for his contribution in the technical front. I am very satisfied to have been able to help Gassco AS with this project and thank them for this opportunity.

I would like to recognize Roy Endre Dahl for his contributions to this thesis as my Investment Analysis professor. These were essential in the mathematical deductions required for this project.

None of this would have been possible without my internal supervisor, Jayantha Prasanna Liyanage. I am extremely grateful for his trust, motivation and advice. I am glad to have been able to look up to him as a mentor.

I feel blessed to have been able to share this experience with so many wonderful peers. I thank them for their company and assistance. Finally, I dedicate this to my family. I thank my mother and sister for their support in this endeavor and their unconditional love. To my father.

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Abbreviations

AU – Asset Utilization

CoC – Cost of Capital

CoUr – Cost of Unreliability

Dc – Direct Costs (of Unreliability)

Ec – Equipment Spare Costs (of Unreliability)

EVA – Economic Value Added

Fc – Financial Costs (of unreliability)

FTA – Fault Tree Analysis

IC – Invested Capital

Ic – Indirect Costs (of Unreliability)

Lc – Maintenance Related Labor Costs (of Unreliability)

LRC – Labor Repair Cost

Oc – Overly Costs (of Unreliability)

OPEX – Operational Expenditure

Pc – Production Costs (of Unreliability)

PV – Present Value

MVA – Market Value Added

n - Lifetime

NCS – Norwegian Continental Shelf

NOPAT – Net Operating Profit after Tax

R – Revenue

RAMS – Reliability, Availability, Maintainability & Safety

RAT – Replacement Analysis Tool

RBD – Reliability Block Diagram

Rc – Reactive Costs (of Unreliability)

R&D - Research and Development

SPC – Spare Part Cost

T – Tax

TR – Tax Rate

1 Introduction

1.1 Background and Challenge Description

Equipment maintenance is an essential part of any industrial plant. Significant resources are assigned to this matter and there is a strong sense of agreement towards its importance. Companies will usually have a special department in charge of maintenance, thus reflecting how crucial this activity is. In a broad sense, the objective of maintenance is to maximize gains and minimize risks. Equipment needs to be operational for as long as possible whilst having the least probability of failure attainable. This will ensure production, and thus revenue, are maximized. On the other hand, risks arising from potential HSE issues and production loss can be controlled. However, this is not to be achieved without a "cost". Every aspect of maintenance has a financial charge associated with it, most of them are really evident. On the contrary, unlike other departments, all financial gains related to maintenance are indirect and tough to identify. (Wintle, 2006)

Challenges are met when attempting to establish a robust decision method to support ageing equipment-replacement (one for one). If supplanting a component truly is beneficial, it is to be seen as an investment. Nevertheless, not all of these actions will generate a positive net present value for the investor. There is a concern towards uncertainties related to potential increased failure rates which would result in shut-downs, production loss and probable high repair costs. But, will these costs truly exceed the value of the investment? (Thus justifying it).

Gassco AS is responsible for safely and effectively transporting natural Gas from the NCS (Norwegian Continental Shelf). It has been noted by the company that in the past, when replacing a significant number of units within a system, a clear financial business driver for such investment has been challenging to quantify. While some cases require a replacement anyhow, due to regulations, it would be convenient to show if they are financially sound. The challenge is to identify and quantify the parameters needed to determine the Net Present Value of a replacement decision. Potential losses are to be weighed against the cost of the investment. If the former exceed the latter, the replacement is financially justified. This master thesis is a result of Gassco's interest in exploring possible solutions on this matter.

1.2 Objective

Aid Gassco AS in developing a fact-based methodology to help support economical decisions pertaining the replacement of selected equipment.

1.3 Scope

This project will seek to develop a fact-based methodology to help support the economic decision process of the company. Particular focus will be placed in the replacement of ageing equipment. Following such methodology must result in obtaining a value that might provide financial justification for maintenance decisions. This value must reflect if an investment is financially sound. Such value shall arise from connecting attainable technical parameters (e.g. downtime, breakdown) to financial performance metrics (e.g. NPV). The methodology should be general enough to be used for several systems within the company.

1.4 Methodology

The objective is to be reached by an iterative process including investigation, modification, testing and evaluation. Firstly, methods shall be investigated. Any pertinent modifications required on them should take place. Testing of the methods with a case should come next with a proper evaluation following.

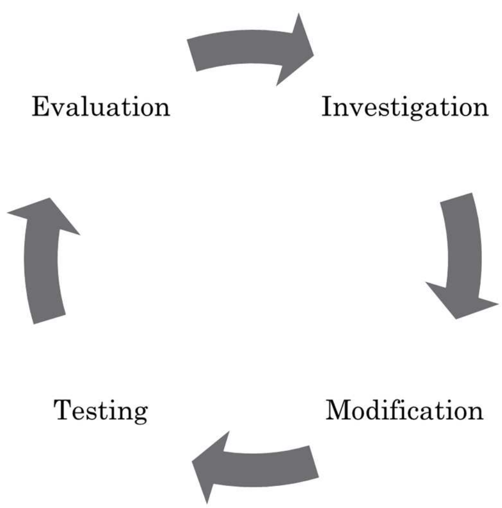


Figure 1: Project methodology

The process should be repeated several times. It is crucial that the objective of the project be kept in mind at all times. This is to develop a fact-based methodology to help in equipment replacement decision-making.

1.5 Limitations

This thesis does not seek to find an ultimate solution to the ageing equipment replacement dilemma. Rather than a full, but conventional solution, a rather partial but unorthodox one is looked for. Replacement scenarios will be limited to specific selected equipment. This will thus exclude whole systems or full assets.

1.6 Thesis Outline

To achieve the objective, after this introductory chapter, the following structure will be followed.

Chapter	Purpose
2	Show the results of a literary survey regarding industry used methods
3	Display the main challenges arising from the literary survey
4	Present a recommended model to achieve the objective
5	Test the suggested model against a mock (hypothetical) case
6	Test the recommended model with a real case
7	Provide a series of proposals for the better use of the suggested model
8	Present the conclusions of the project

Table 1: Thesis outline

The necessary attachments shall follow at the back end of this written report.

2 Literary Survey

2.1 A Foreword on Maintenance Management

Maintenance management concerns itself with overseeing the use of resources for assuring the continuous operation and productivity of a plant. This involves working on facilities and equipment to ensure they are not only operational, but also compliant to local and external regulations. Guaranteeing these conditions involves a great deal of scheduling to avoid expense or production-loss peaks. In able to accomplish this, a maintenance system is needed. These are designed according to circumstances and experience along with decision-tools and techniques. Planning, organizing, controlling and implementing the maintenance strategy is the main goal of the system. The bottom-line is to help the company be as productive as it can. (Ben-Daya, 2009)

Productivity is a ratio between the output and input of the system. In a general sense, the purpose of any business is to obtain as much out of it with as little intake as feasible. This depends on a tremendous amount of factors, maintenance being one of them. In the process industry, maintenance seeks to keep production at high levels by preserving the condition of the components present in the plant. Moreover, maintenance management is also concerned with suggesting measures for the improvement of the overall process. (Ben-Daya, 2009)

Every component of a system has an expected operation lifetime. As time goes by, it is expected that its performance gradually declines and its failure-probability increases. It is evident that equipment inevitably needs replacement at some point, but, how can one determine when it is most convenient to do so? These decisions have to account for a multitude of considerations: acquisition costs, expected revenue increase, fiscal incentives, obsolescence, alternatives, reliability change, etc. (Kelly, 2006)

2.2 Equipment Replacement Decisions

In able to make sound replacement decisions, information is required. Numbers linked to future repair costs and failure probabilities have to be compared to the current ones. The replacement investment cost is to be factored in as well. The more data available and the better the methods used to process it, the finer the decision-assistance will be. Nonetheless, obtaining such information is resource consuming. Time and financial assets are not always at one's disposal. There are also scenarios in which the attainment of certain statistics is extremely challenging. (Chanter & Swallow, 2008)

If the circumstances justify it, an analytical approach might be taken. In such, a discounting exercise is carried out. Potential replacement costs are turned into an annual cost and added to the expected repairing costs of the new item. Then they are compared to the repair costs expected if nothing is done. Both cases are discounted to present value and "annualized". The real challenge is in the execution details. All costs previously mentioned are dependent on system reliability and performance. These are dynamic and depend on a series of interconnected sub-systems and components for which the required data may not be available. (Chanter & Swallow, 2008)

Due to these challenges, the analytical approach is not the only one available to determine if a replacement is to be made. Maintenance replacement policy exists in the spirit of aiding decision-makers avoid major negative consequences by setting fix equipment replacement periods. This is a conservative approach, it is only natural to question if it is not one that requires severe over-spending. Yet, it is clear keeping on the safe side of things in the face of uncertainties is wise. It is not always possible to obtain direct and clear financial decision-making support for equipment replacement. Depending on the situation, the overall sense of need for a replacement can differ greatly. (Chanter & Swallow, 2008)

There are several scenarios that will drive a maintenance manager to replace an equipment.

1. Equipment failure or damage has rendered the equipment useless and it cannot be repaired
2. Performance is below the operational output requirement (can cause a bottleneck)
3. An imminent an unacceptable safety risk has been identified on the equipment
4. A clearly better alternative is now available on the market
5. Equipment support (spares, service, etc.) is hardly available
6. External regulations mandate replacement
7. Internal regulations mandate replacement
8. Vendor deems equipment obsolete

The items above are enlisted in decreasing "visibility"; the first ones do not require much analysis and would be done almost automatically, while the last ones would at least go through some questioning process. It can be noted that the cases on top of the list are ones in which either potential gain opportunities or loss risks are easily perceptible and calculable. As the list goes further down, this is completely the opposite.

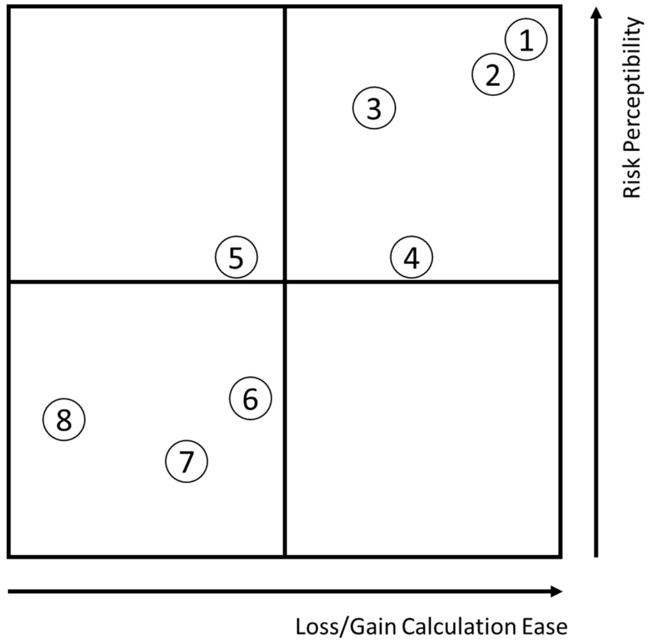


Figure 2: Equipment replacement driver strength

Figure 2 shows an estimate of the drive strength to replace equipment for each case enlisted above.

The focal point of this project will be the bottom-left quadrant. Gassco AS has expressed concern in the handling of these cases. Ones in which uncertainties are not easily perceptible and calculating potential gains or losses are far from easy. Such scenarios are candidates for a robust analytical approach if their cost is high enough. This work will target situations in which the level of replacement expenditures is high enough to favor the use of resources for an analytical approach. The industry has had to deal with this for decades. Findings pertaining industrial "best-practices" or methods for dealing with this predicament are evaluated next.

2.3 Findings on Industry-Used Maintenance Technical Tools

2.3.1 Reliability and Failures

In able to follow and accomplish its maintenance strategy, the industry has several well-known, tools and techniques at its disposal. In able to properly understand them, one must firstly introduce the concept of reliability. Reliability engineering has the purpose of developing tools and methods to evaluate and demonstrate the reliability, availability, maintainability and safety (RAMS) of components, equipment and systems. The expectation for plant managers would be to have equipment operate failure free when introduced into the system (when new) and for the rest of its lifetime. The question then arises, will this equipment fail within a given period of time? It turns out this cannot be simply answered with a "yes" or "no". Only a probability for this can be given. This probability is a measure of the item's "reliability". (Birolini, 2014)

Formally, "If n statistically identical and independent items are put into operation at time $t = 0$ to perform a given mission and $v \leq n$ of them accomplish it successfully, then the ratio v/n is a random variable which converges for increasing n to the true value of the reliability" (Birolini, 2014, p. 2). This means that for large samples of identical components under identical conditions, the reliability indicates the percentage of them that will function without operational interruptions during a stated time interval. (Birolini, 2014)

Reliability is only hindered when an equipment's operation is interrupted. This is important to keep in mind, since not all defects in a system will lead to interruptions. If an equipment has a defect, but it does not result in interruption, it is referred to as a "fault". On the other hand, "...failure occurs when the item stops performing its required function" (Birolini, 2014, p. 3). These can occur suddenly or gradually depending on the nature of the component at hand. Failures are further classified according to their mode, cause, effect and mechanism. The mode is the failure symptom by which it is identified (e.g. crack). Causes can be intrinsic or extrinsic, the former referring to the material of the equipment (e.g. material weakness) and the latter due to operation misuse (e.g. pump operation without lubrication). Effects can be limited to the item itself or extended to further parts of the system. Generally, according to their impact, they are classified as: non-relevant, partial, complete and critical. They is also a distinction between primary and secondary effects since some failures can cause further ones. Finally, mechanisms refer to physical or chemical processes resulting in a failure (e.g. corrosion). All these classifications help in the prevention and mitigation of failure, this is in turn reflected in a decrease in the frequency in which failures occur. (Birolini, 2014)

A very common practice to make the most out of a failure analysis is the Failure mode, effects and criticality analysis (FMECA). This analysis helps determine the relationships between components within a system. It is used to identify the most critical portions of a structure and is thus excellent as an aid to determine how to prevent or mitigate failure. This can be done by adding barriers or safeguards (e.g. redundancy, monitoring, etc.). These models are also essential to avoid failure propagation; by completing such analysis, potential secondary failures can be identified and dealt with. Appendix A shows an FMEA example as a reference. (Group, 2007) (Birolini, 2014)

2.3.2 Failure rate

The pace at which failures occur is referred to as failure rate. In reliability engineering, this is usually represented by "λ" [h^{-1}]. The higher this number, the unlikelier a failure is. It basically projects the amount of hours it would take in average for one failure to occur. Depending on the equipment, this parameter can be dynamic and thus change across its lifetime.

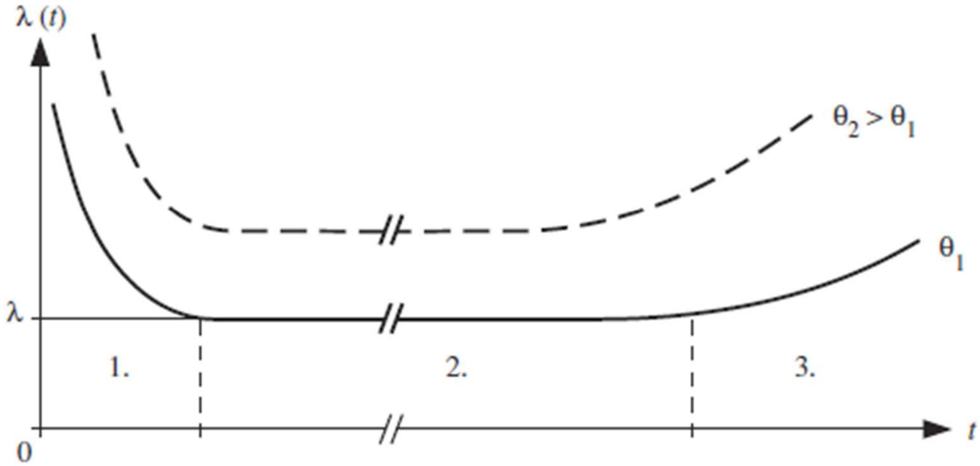


Figure 3: Typical failure rate shape (Identical, independent and nonrepairable items) [dashed is a possible shift for a higher stress, e.g. higher temperature] (Birolini, 2014, p. 7)

Figure 3 shows one of the more typical behaviors of failure rate along the lifetime of a component. This type of curve shape is referred to as "bathtub" curve in maintenance and reliability engineering. It shows three different phases, marked in the figure as zones 1, 2 and 3. The first zone sees a high failure rate at time zero that decreases rapidly. The phenomenon of a relatively high number of components failing in this span is known as "infant mortality". Zone two presents a constant failure rate while zone three has an increasing one. Zone three is usually a state in which equipment is already exceeding its designed lifetime. Equipment providers will normally recommend replacement at a point in time where they estimate the apparatus is still within zone two but close to entering the third one. (Birolini, 2014)

The reciprocal value of the failure rate is known as mean time before failure (MTBF). It is the mean time that elapses between failures. MTBF can be further broken down into mean time to failure (MTTF) and mean time to repair (MTTR). MTTF expresses the time that passes between the end of a failure and the beginning of a new one. MTTR represents the mean time it takes to repair a failure.

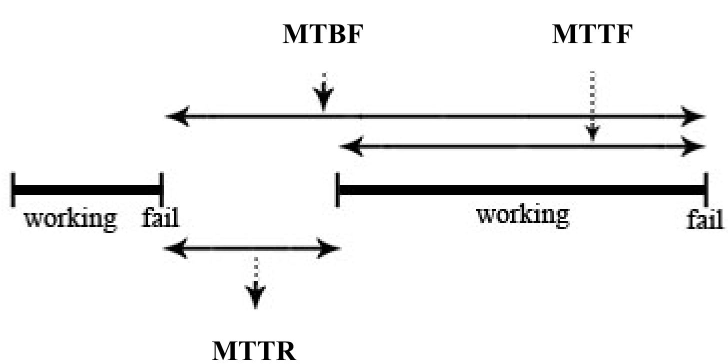


Figure 4: MTTF, MTTR & MTBF (UCLA, 2008)

$$\mathrm{MTBF} = \mathrm{MTTR} + \mathrm{MTTF} \quad (1)$$

$$\frac{1}{\lambda} = MTBF \quad (2)$$

Where:

- MTBF: Mean time before failure
- MTTR: Mean time to repair
- MTTF: Mean time to failure
- λ: Failure rate

These four parameters are the basis in determining the reliability of a component. Failure rate is the required variable, however, in practice, it is usually MTTR and MTTF that are recorded. With them, MTBF can be obtained and thus λ. For many practical applications, the reliability of a component can be determined with the following expression (Birolini, 2014):

$$\mathrm{R(t)} = \mathrm{e}^{-\lambda \mathrm{t}} \quad (3)$$

Where:

- R(t): Reliability as a function of time
- e: Natural logarithm constant (~2.71)
- λ: Failure rate
- t: Time period of evaluation

This expression is valid for components that operate continuously, that are repairable, function "as good as new" after repair and are memoryless. The reliability of individual items is important in able to estimate how often they will require maintenance, however, reliability engineering concerns itself with determining this for equipment, sub-systems and full systems. Doing so requires a careful analysis of the relationships between the components of a system followed by a graphical representation of them. Finally, a quantitative assessment can be performed.

Another useful concept is that of "availability". While reliability showcases the probability that an item will perform its desired task without interruption for a given time (e.g. that a bulb gives out continuous light for 1 year), availability represents the fraction of time a system is "operational". (Systems)

$$\mathrm{A} = \frac{\mathrm{Uptime}}{\mathrm{Uptime} + \mathrm{Downtime}} = \frac{\mathrm{MTTF}}{\mathrm{MTTF} + \mathrm{MTTR}} = \frac{\mathrm{MTTF}}{\mathrm{MTBF}} \quad (4)$$

Where:

- A: Availability

- MTTF: Mean time to failure
- MTTR: Mean time to repair
- MTBF: Mean time before failure

Example I

As aforementioned, usually it is MTTR and MTTF that are measurable. According to the measured data of a particular component "X":

- MTTF: 5000 hours
- MTTR: 10 hours

According to (1) & (2)111:

$$MTBF = MTTR + MTTF = 5000 + 10 = 5010 \text{ hours}$$

$$\lambda = 1/MTBF = 1.996 \text{ x } 10^{\wedge -4} \text{ hours}^{\wedge -1}$$

Considering now (3) for t = 1 year:

$$R(t) = e^{\wedge -\lambda t} = e^{\wedge -(0.0001996*365*24)} = 0.174 \ (17.4\%)$$

Meanwhile, according to (4):

$$A = MTTF/MTBF = 5000/5010 = 0.998 \ (99.8\%)$$

It can be noted that while availability is really high, reliability is not even close. This is because reliability is time dependent and indicates the possibility of a component operating flawlessly for a determined period of time. The shorter the time period used for calculation, the higher the reliability and vice versa. The above reliability result should be read as, there is a 17.4% that the component at hand operates for one year without a single interruption (not a single failure). Meanwhile, availability simply indicates the percentage of time that such component is operational. The above availability result reads as, the fraction of time that the component at hand is properly functioning.

It is worth mentioning that while high availability is usually regarded as positive, for identical availability values, the reality can be significantly different.

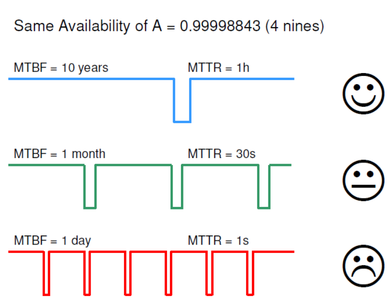


Figure 5: Different MTBF values for the same availability (Systems)

Figure 5 below demonstrates this phenomenon. Even if the overall availability is the same for all three cases above, the one with the least number of failures is more appealing. This is because repair will rarely be needed, monitoring will be unlikely necessary and if other components' functionality depend on this item, it will be hindered much less often, also reducing the probability of bigger consequences due to failure combination.

2.3.3 Reliability Block Diagrams

One of the ways of graphically representing the relationships between individual items of a system is with a reliability block diagram (RBD). RBDs are event diagrams, they indicate which components of the system are necessary for the fulfillment of the task and which can fail without affecting its completion.

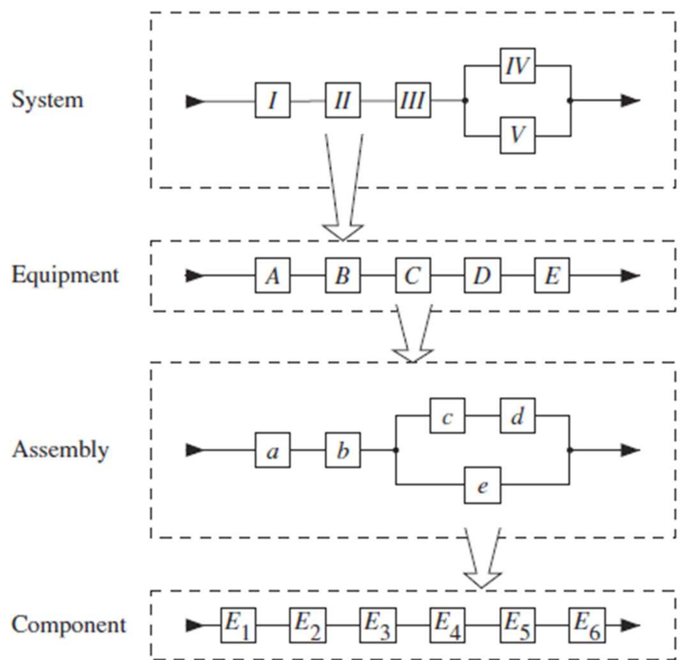


Figure 6: Procedure for setting up a reliability block diagram (RBD) of a 4-level system (Birolini, 2014)

Figure 6 is an excellent reference as a help to understand the nature of RBDs. There are four levels (bottom to top): component, assembly, equipment, system. Each upper level can be broken down into several of its lower peers. The system RBD is composed of five blocks: I, II, III, IV and V. Block II is then broken down into the RBD shown in the equipment level, composed by A, B, C, D and E. C is then extended into the assembly level containing a, b, c, d and e. Finally e is broken down into the component RBD that includes E1, E2, E3, E4, E5 and E6. In this figure, only a portion of the total RBDs are shown; from the system into the equipment level, not only II can be broken down, but the other four items also. This is also true from the equipment to the assembly level and into the component one. Normally one starts by building RBDs for the lower levels and climbs up until the upper level can be built.

One of the things that one can notice easily from RBDs is that blocks can be either connected "in series" or "in parallel". Calculating the reliability for each type of system has significant differences.

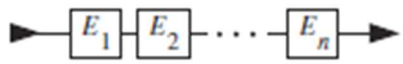


Figure 7: Series structure RBD (Birolini, 2014)

In this case, calculating the reliability of Figure 7 is done as follows:

$$\mathrm{RS} = \prod_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{Ri} \tag{5}$$

Where:

- RS: Reliability of the system
- i: Number of items
- n: Total number of items
- Ri: Reliability of «i» component

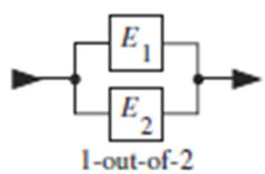


Figure 8: Parallel structure RBD (Birolini, 2014)

For Figure 8, the calculation of the system's reliability is done as follows:

$$\mathrm{RS} = \mathrm{RE1} + \mathrm{RE2} - \mathrm{RE1} * \mathrm{RE2} = 1 - [(1 - \mathrm{RE1}) * (1 - \mathrm{RE2})]$$

In case more than two elements in parallel are present, then the easiest way to calculate the system is:

$$\mathrm{RS} = 1 - \prod_{\mathrm{i}=1}^{\mathrm{n}} (1 - \mathrm{Ri}) \tag{6}$$

There are other types of RBD structures (see Appendix B for further details), however, the two previously presented are the most common ones. Determining which structure to use depends on the characteristics of the system analyzed. FMECAs can be really useful in able to do this. If two elements of the system are present:

- Chose a *series structure* if system failure occurs when *any* of the components fail

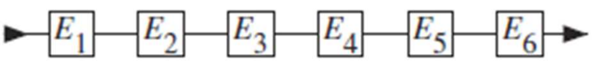
- Chose a *parallel structure* if system failure occurs when *both* of the components fail

An important concept when working with RBDs is that of "minimal cut set". A minimal cut set is a minimal set of reactions whose inactivation would guarantee a failure in a system. For example, in Figure 6's assembly, the minimal cut sets are [a]; [b]; [c, e]; [d, e].

Example II

Take Figure 6 as a reference. One starts at the lower level (component). There are six components in it, one will assume the following reliabilities (one year for all) for them:

- E1 = 0.90
- E2 = 0.95
- E3 = 0.99
- E4 = 0.98
- E5 = 0.97
- E6 = 0.92

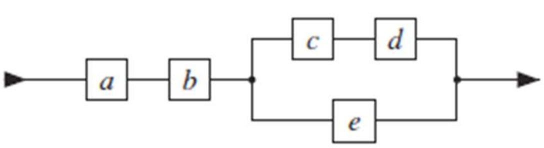


Since this is a series arrangement and according to (5):

RS = E1*E2*E3*E4*E5*E6 = (0.90)*(0.95)*(0.99)*(0.98)*(0.97)*(0.92) = 0.74 (74%)

This provides the value for the "e" block at the assembly level. Analogous calculations would be done for a, b, c and d as well. For illustration purposes they will be assumed, thus:

- a = 0.88
- b = 0.91
- c = 0.93
- d = 0.89
- e = 0.74



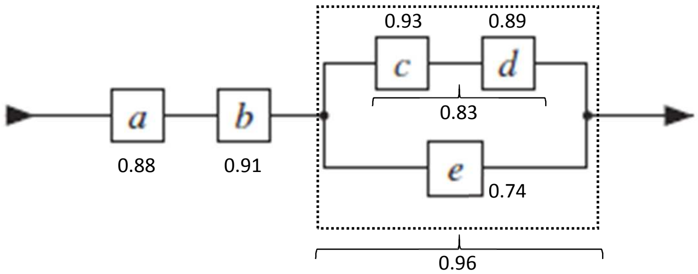
This level has both series and parallel arrangements; one has to solve this in parts. Starting with the reliability of the series formed by c and d.

Rc-d = 0.93*0.89 = 0.83

Next, one calculates the reliability of the parallel structure formed by c-d and e. According to (6):

Rcd-e = Rc-d + Re – (Rc-d *Re) = 0.83 + 0.74 – (0.83*0.74) = 0.96

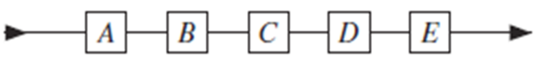
Finally one gets the reliability of the whole structure with Ra, Rb and Rcd-e as a series.



RS = Ra*Rb*Rcd-e = 0.88*0.91*0.96 = 0.77 (77%)

This provides the reliability for the "C" block in the equipment level. There are a total of five blocks in this level, assuming the reliabilities for the other blocks:

- A = 0.98
- B = 0.92
- C = 0.77
- D= 0.91
- E = 0.89



Considering the series structure:

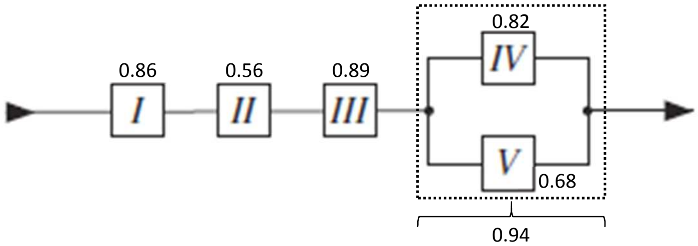
RS = RA*RB*RC*RD*RE = 0.98*0.92*0.77*0.91*0.89 = 0.56 (56%)

This provides element's II reliability at the system level. Assuming the rest of the reliabilities:

- I = 0.86
- II = 0.56
- III = 0.89
- IV = 0.82
- V = 0.68

IV and V form a parallel structure for which reliability is 94% (0.82+0.68 – 0.82*0.68). Taking this as part of a series structure together with I, II and III:

RS = RI*RII*RIII*RIV-V = 0.86*0.56*0.89*0.94 = 0.4 (40%)



After following the whole process it has been determined that the whole system has a reliability of 40%. It is important to note that this reliability is exclusive for a time-frame of 1 year. Using (3) one can determine the failure rate of the whole system:

$R(t) = e^{-\lambda t}$; ln(R(t)) = -λt; λ = -ln(R(t))/t; R(t) = 0.4; t = 1 year

λ = -ln(0.4)/1 = **0.9163 failures/year**

Using (2):

$\frac{1}{\lambda} = \boldsymbol{MTBF}$ = 1.01913 years/failure = **9560.28 hours/failure**

If one can manage to measure the MTTR of equipment in this system and it is found to be ca. 40 hours/failure, MTTF can be calculated with (1) and is equal to 9520.28 hours/failure. Availability can also be calculated with (4):

$$\mathbf{A} = \frac{Uptime}{Uptime + Downtime} = \frac{\text{MTTF}}{\text{MTTF+MTTR}} = \frac{\text{MTTF}}{\text{MTBF}} = 9520.28 / 9560.28 = \mathbf{99.582\%}$$

The downtime for 1 year in hours is obtained by simply multiplying MTTR times the failure rate:

Downtime = MTTR*λ = 40*0.9163 = **36.65 hours/year**

2.3.4 Fault Tree Analysis

Whenever analyzing particularly complex or detailed systems, the fault tree analysis (FTA) is one of the more useful tools available. This is a systematic approach to model different failures that can occur in a system in a top-down hierarchical manner. Failures are associated through logical gates depending on their interdependencies. This technique enables to highlight the logical combinations of faults required for a particular event to happen. It is graphically represented as a tree. FTAs are very intuitive tools for modelling system availability. (Flaus, 2013) (Taylor & Ranganathan, 2013) (Vincoli, 2014)

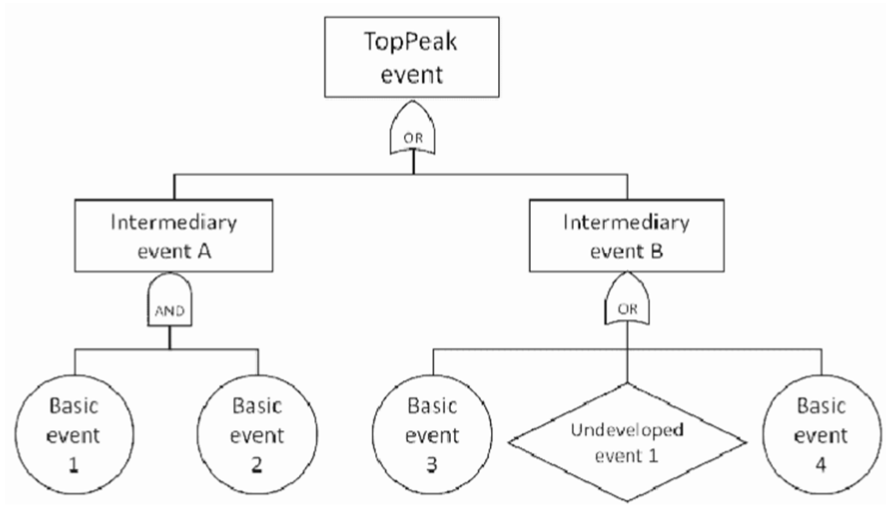


Figure 9: Example of a fault tree (Flaus, 2013)

A fault tree contains two basic elements, events and logic gates. An event is a fault or failure that triggers a logic gate. There are four basic types of events: top, intermediary, basic and undeveloped. Taking Figure 9 as a reference, we can identify all of them. Basic events are at the roots of the tree, they are ones that cannot be further split into others. Undeveloped events are also at the roots. They are not basic events as they could be expanded. However, due to lack of information or difficulty in developing them, they remain as such. Intermediary events are any of them between the basic level and the top. Figure 9 only shows three levels, however, depending on what is being analyzed, an FTA can have many more. The top event is the reason why the FTA is carried out. It represents the development that would occur if certain conditions of the tree are met. Generally, FTA top events are undesired situations and therefore all lower levels are faults, nonetheless, the model can also be used for desired outcomes. (Taylor & Ranganathan, 2013)

Events in an FTA are connected by gates. There are two main types of gates, “and gates” and “or gates”. They are an integral part of the analysis and define the relationships between the different events across all levels. These gates characterize basic digital logic. When an “and gate” is used, it indicates all events connected to it from the bottom must occur in able for the gate to trigger the event connected to it from the top. When an “or gate” is used, it indicates only one of the events connected to it from the bottom must occur for it to trigger the event connected from the top. In Figure 9 for example, both basic event 1 and 2 must occur for the Intermediary Event A to happen. On the other hand, if either basic event 3 or 4 or undeveloped event 1 happen, the Intermediary Event B will take place. (Taylor & Ranganathan, 2013) (Vincoli, 2014)

It is important to note that the previously described event types and gates are only the more common ones. For a more extensive list of events and connectors please refer to Appendix C. The methodology for building an FTA is fairly straightforward, but it can be significantly time consuming.

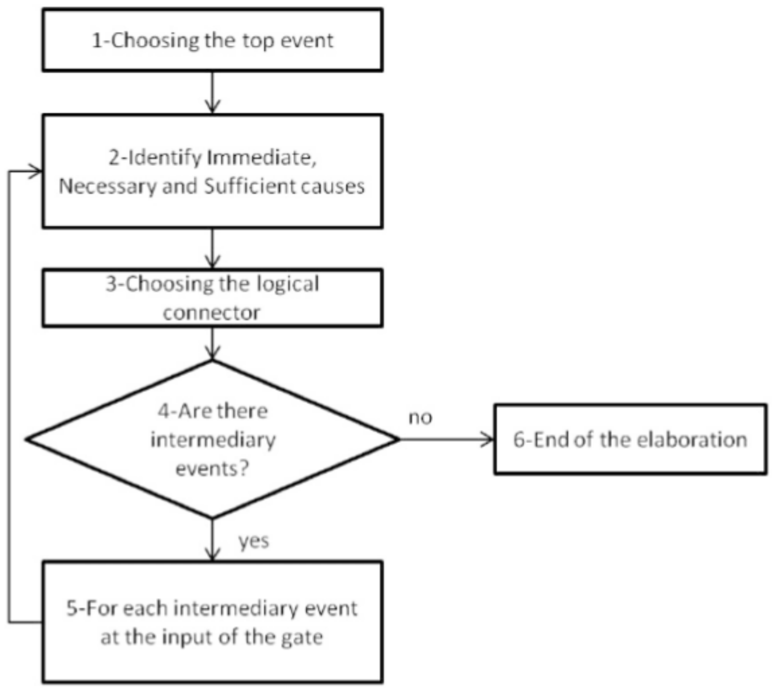


Figure 10: Steps for building a fault tree (Flaus, 2013)

For illustration purposes, the process of building a simple FTA will be shown. As Figure 10 indicates, the first step is to select a top event within a system. As an example, a gas powered vehicle will be chosen. The top event will be "the car cannot be started". Now step number two shall be carried out, all events that could lead to the top event are enlisted below.

- No gas
- No electric power
- Cannot find keys

Using the above events and choosing the appropriate connector according to step three an initial tree can be built.

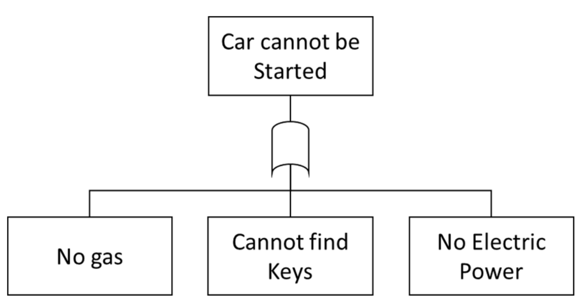


Figure 11: Initial (Incomplete) FTA

The question now is, according to step four, are there any intermediate events? Checking Figure 11 one can determine that two out of the three events could be further expanded and are therefore intermediate. "Cannot find keys" will be considered as a basic event. The other two will be split into the following.

- No gas (and gate)
  - Empty tank
  - No spare gas
- No Electric Power (and gate)
  - Dead Battery
  - No electrical backup (or gate)
    - No jumper cables
    - No second car with battery

Steps two and three are repeated. Note that gate-type selection is crucial. For a "no gas" event to be triggered, both an empty tank and no spare gas have to occur. Similarly, "no electric power" occurs when both the battery is dead and there is no backup. In these two cases "and gates" are used. On the other hand, an "or gate" is used when no electrical backup happens. This is because when either no jumper cables are available or there is not another car to jump the battery from the "no electrical backup" event occurs.

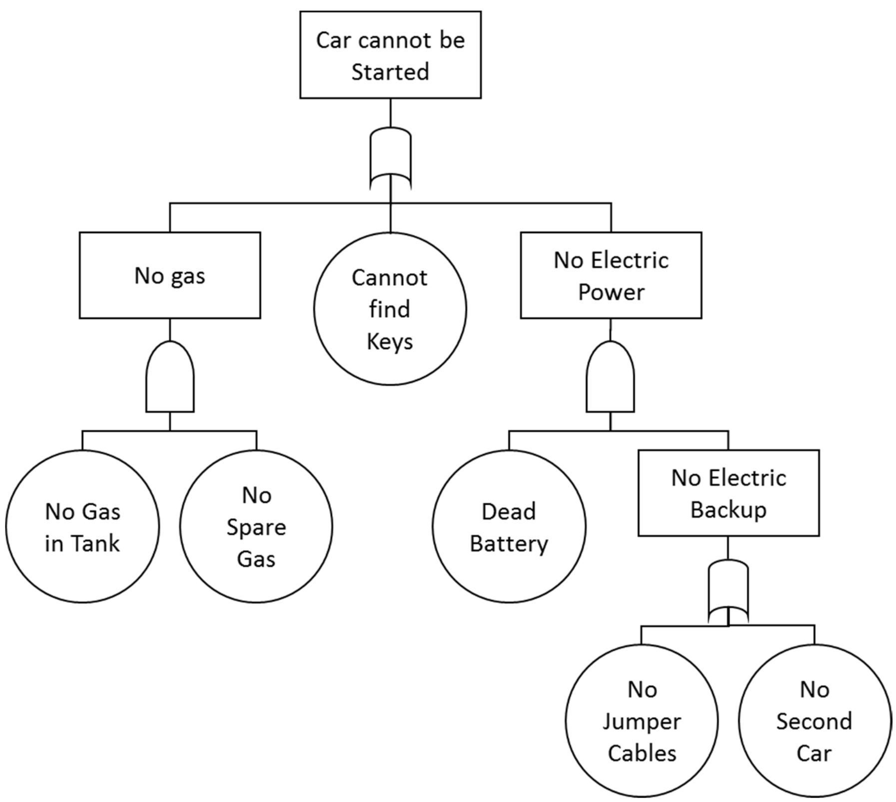


Figure 12: FTA Building example

Step four is once again carried out, but being that no more intermediary events are found at the lower level, the tree can be considered complete (step six). Note that this is a simplified example, some events here presented as basic could be further split. For example, "No Gas in Tank" could be an intermediary event connected to the top of an or gate that connects basic events like "all gas consumed by combustion", "tank leak", "gas stolen", etc.

Fault trees have a significant qualitative value, since they help understand the interdependencies between events. Once this is done, preventive and mitigation measures can be put in place to lower the chances of reaching the undesired top event. FTA has also a quantitative nature though. The probability of the top event occurring can be calculated from the bottom up. The calculation method to be used depends on the logical gate one has to go through.

$$P_{Or} = \sum_{i=1}^{i=n} Pi - JP \tag{7}$$

$$P_{And} = \prod_{i=1}^{i=n} Pi \tag{8}$$

Where:

- P_{Or}: Probability of upper event through an "or gate"
- P_{And}: Probability of upper event through an "and gate"
- P_i: Probability of lower event "i"
- n: Total number of lower events
- JP: Joint Probability (this is zero for mutually exclusive events)

JP accounts for the possibility of having joint probabilities. These are cases in which two or more lower events can happen at the same time.

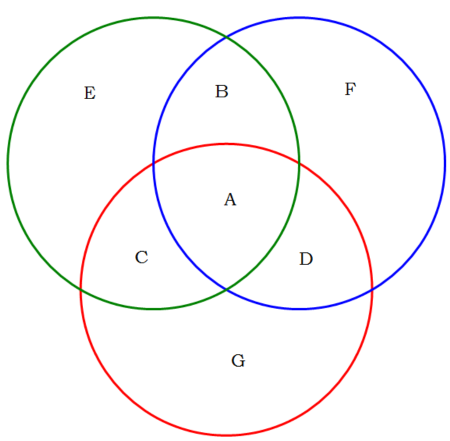


Figure 13: Three circle Venn diagram

Let us use Figure 13 to exemplify this. Let the red circle represent P1, the green P2 and the blue P3. If one uses (7) and disregards JP.

$$P_{Or} = P1 + P2 + P3$$

However, if one does so, section A will be counted 3 times (2 more than it should), while sections B, C and D will be counted 2 times (1 more than they should). One needs to subtract A two times and B, C & D once. The JP variable accounts for this. P1*P2*P3 gives A. P1*P2 gives A + C. P2*P3 gives A + B. P1*P3 gives A + D. P_{Or} would then be adjusted to:

$$P_{Or} = P1 + P2 + P3 – [2*P1*P2*P3 + P1*P2 + P2*P3 - P1*P3]$$

For 2 event cases that are not mutually exclusive, the expression is simplified to:

$$P_{Or}: P1 + P2 – P1*P2$$

Example III

To typify the calculation process through an FTA, we will go back to Figure 12. The probability of all basic events is known. The objective is to find the probability of the top event.

Basic Event	Probability
No Gas in Tank	0.005
No Spare Gas	0.900
Cannot find Keys	0.008
Dead Battery	0.005
No Jumper Cables	0.300
No Second Car	0.100

Table 2: FTA Example basic event probabilities

Table 2 contains the probability of the basic events happening in the next year (1 year unreliability).

To find the probability of "no electric backup" (or gate) considering non-mutually exclusive events.

$$Pneb = 0.3 + 0.1 – (0.3*0.1) = 0.37$$

Combining this with the probability of a dead battery through the "and gate" yields the "no electric power" event.

$$Pnep = 0.37*0.005 = 0.00185$$

To obtain the "no gas" event, the "no gas in tank" and "no spare gas" basic events must be combined through an "and gate".

$$Png = 0.005*0.9 = 0.0045$$

Finally, the top event is obtained combining Png, Pnep and the "cannot find keys" event through an "or gate". For simplicity, these three will be considered mutually exclusive (JP = 0)

$$P_{(top\ event)} = 0.0045 + 0.00185 + 0.008 = 0.01435$$

FTAs can also be formulated to use other parameters in them like failure rate or availability instead of reliability (or unreliability). Taking this into account, this is a powerful and versatile tool. Whenever a component is replaced, the result obtained for the top event will most likely change. If the more critical components are substituted with more reliable ones, the end result could be extremely beneficial.

2.4 Findings on Industry-Used Economic Models

Justifying an equipment replacement decision is far from simple. Thus, several efforts have been made in the industry to determine which cases warrant a replacement. As part of this thesis, research was carried out to try to find any methods currently in use for this purpose. In line with the objective of this project, any approach that is to be considered has to provide quantitative decision-support. Any spending made on replacing equipment has to be seen as an investment; it shall only be made if one is expected to get a return from it.

2.4.1 Discounted Cashflows (DCF)

Some of the most universally used methods to determine if an investment is worthwhile are based on discounted cashflows (DCF). Whenever investing, one has to consider the magnitude, timing and degree of uncertainty of future cashflows. The larger, faster and most certain the cashflows are, the better. The DCF approach projects expected future cashflows and "discounts" them at a rate of return that reflects the perceived risk they have. Such rate reflect the "time value" of money and a "risk premium" that shows the return investors need to compensate them for the danger of the cashflow never materializing. (Young, 2001)

$$\mathrm{NPV} = \sum_{t=1}^{t=n} \frac{\mathrm{CF_t}}{(1+\mathrm{r})^{\mathrm{t}}} \tag{9}$$

This gives out the net present value (NPV) of a project. Investment is also to be considered as a cashflow. If NPV is positive, it means the sum of all cashflows will result in a gain and the investment makes sense. If negative, one will incur in losses and should back away from the investment. Another way to use the DCF approach is by figuring out the maximum discount rate that a project can handle without its NPV going into negative. This yields the internal rate of return (IRR). If IRR is higher than the discount rate, the project should be accepted.

(Young, 2001)

Example IV

There is an investment opportunity that requires $10,000 up front. At the end of each of the following 5 years, a positive cashflow is expected (already considering revenue, expenditures, taxes, etc.). An investment advisor considers using a discount rate of 10% would be adequate.

Year	Cashflow
0	-10000
1	1500
2	2500
3	5000
4	3000
5	1500

Table 3: Cashflows example

The investment is considered as a negative cashflow at the end of "year 0" and then (9) is used.

NPV = -10000 + 1500/((1+ 0.1)^1) + 2500/((1+ 0.1)^2) + 5000/((1+ 0.1)^3) + 3000/((1+ 0.1)^4) + 1500/((1+ 0.1)^5) = **$166.75**

According to this result, the investment should be made. If the IRR is sought with the help of iterative software, the answer will be 10.63%. Since the discount rate is 10%, the IRR technique also indicates to accept the investment.

2.4.2 Economic Value Added (EVA)

The NPV and IRR methods are very well known and extremely useful. They are great as an initial reference point before considering any detailed analysis and time-consuming calculations. They are easy to grasp and are thus well accepted by managers, however, they are limited when compared to more powerful models. The concepts that DCF considers are nevertheless acknowledged in almost any methodology.

"Economic Value Added" (EVA) works under the fundamental fact that one can only get richer if one invests money at a higher rate than the cost of having obtained that money. Furthermore, a company, just like an individual, shall not make an investment unless it gives back at least the same level of return rate as a similar alternative. This essentially means that if a loan is obtained with the intention of investing, one should only do so in projects that not only cover back the interest rates to be paid for the loan, but also the expected rate of return obtained in a similar (safer) opportunity. (Stern, Shiely, & Ross, 2002)

This technique is used to "capitalize" spending that is usually "expensed". Some typical examples are marketing, R&D or training. In accounting terms they are normally just considered expenses; mostly in able to reduce the yearly tax burden on the company. However, in practical terms, not much different from facilities or equipment, they are an investment with an expected lifetime and added benefits. What if they were capitalized as an investment and discounted over their lifetime, would it be better in terms of calculating their true impact for the company? Can maintenance also be one of the spending columns that can transition from being "expensed" into being "capitalized"? If so, it could be of great assistance in achieving this project's objective. (Stern et al., 2002)

"EVA is defined as net operating profit after tax (NOPAT) less a capital charge that reflects a firm's cost of capital."(Stern et al., 2002, p. 19) A great feature of EVA is that it is flexible enough to be used at different levels of a company's structure. This means it can be calculated for the company as a whole, or for only a division or even only a product line. (Stern et al., 2002)

EVA is a cashflow, it is a measure of profit. The main difference from a typical accounting measure is that this is "economic" profit rather than an "accounting" one. This is because revenues must be sufficient to cover both operating costs and capital costs, including equity finance costs (costs of having shareholders that expect a return). Without economic profits, one cannot create wealth for investors. (Young, 2001)

$$EVA = NOPAT - CC \tag{10}$$

Where:

- NOPAT: Net operating profit after tax
- CC: Capital charge

$$NOPAT = R - OPEX - T \tag{11}$$

Where:

- R: Revenue
- OPEX: Operational expenditure
- T: Taxes

$$CC = IC * (CoC) \tag{12}$$

Where:

- IC: Invested capital (capital value of company, department, production line, etc.)
- CoC: Cost of capital

Combining (10), (11) & (12), the economic value added is calculated as:

$$EVA = R - OPEX - T - IC * CoC \tag{13}$$

EVA can be very dynamic and suffer significant changes from year to year. This is because analogous to the DCF approach, additional negative flows (mainly investments) require some time to be recovered. It is therefore unwise to always try to keep a high EVA. The real goal is to make sure one maximizes the present value of future EVAs. When these are discounted and summed, the "Market Value Added" (MVA) is obtained.

$$MVA = \sum_{i=1}^{n} EVA_i \tag{14}$$

(13) Can be divided in two parts and expressed as:

EVA = R – [OPEX + T +IC*CoC]

Where the revenue is the first part and is expected to rise whenever an investment is made. The second part is also expected to increase with an investment. While taxes will not necessarily rise, OPEX is more often than not going to do so, and the Invested Capital will inevitably become higher. EVA will only increase if the revenue part of EVA outgrows the second part composed of OPEX, Taxes and IC*CoC.

Example V

A company is trying to decide if it should make an important investment at the end of this year. Its alternative is to not carry out the investment at all. The objective is to maximize MVA from year's end (Year 0) to five years afterwards (Year 5). For simplicity, the company will be assumed to currently have no debt and to pay all its profit as dividends to its shareholders (no additional capitalization of profit as reinvestment). The company's capital is currently $110,000. The investment amount required is $50,000. Of that, $30,000 will be capitalized right from the start, the rest is to be used as operating capital. After a detailed analysis, a group of experts come up with the following expected values for revenue and OPEX.

Year	Without Investment		With Investment	
	Revenue	OPEX	Revenue	OPEX
1	50000	12000	40000	35000
2	48000	13000	55000	35000
3	45000	14000	75000	35000
4	38000	16000	90000	37000
5	30000	17000	90000	37000

Table 4: Example V information

The current Cost of Capital of the company is 10%. If the investment is carried out, it would rise to 12% to account for a higher risk factor. If the investment is to be carried out, an amortized 5 year loan @ 7% yearly will be used. Inflation is negligible. The company has a tax regime that requires it to pay 35% of its profits.

Let us start with the case without investment. The objective is to find MVA, which is the sum of the present values of all future 5 EVAs.

Year	Discounted [CoC = 10%; Initial IC = 110000]							
	Revenue	OPEX	Profit	Taxes	NOPAT	IC	IC*CoC	EVA
1	45454.5	10909.1	34545.5	12090.9	22454.5	100000.0	10000.0	12454.5
2	39669.4	10743.8	28925.6	10124.0	18801.7	90909.1	9090.9	9710.7
3	33809.2	10518.4	23290.8	8151.8	15139.0	82644.6	8264.5	6874.5
4	25954.5	10928.2	15026.3	5259.2	9767.1	75131.5	7513.1	2253.9
5	18627.6	10555.7	8072.0	2825.2	5246.8	68301.3	6830.1	-1583.3
							MVA =	**$ 29,710**

Table 5: Example V MVA calculation without investment

Note that all flows are discounted at 10% in Table 5. Even the Invested Capital is discounted and as a result the capital charge declines over time. The MVA is close to $30,000. Let us now compare this to the case where the investment is made.

Year	Discounted [CoC = 12%; Initial IC = 140000]							
	Revenue	OPEX	Profit **	Taxes	NOPAT	IC	IC*CoC	EVA
1	35714.3	34281.2	-1598.0	-559.3	-1038.7	125000.0	12500.0	-10507.6
2	43845.7	27901.8	13774.3	4821.0	8953.3	90909.1	9090.9	2032.0
3	53383.5	24912.3	27041.0	9464.4	17576.7	82644.6	8264.5	10742.4
4	57196.6	23514.2	32884.5	11509.6	21374.9	75131.5	7513.1	14659.7
5	51068.4	20994.8	29813.9	10434.9	19379.1	68301.3	6830.1	12808.6
							MVA =	**$ 29,735**

**interest payments are deducted from profit

Table 6: Example V MVA calculation with investment

In this case, flows are discounted at 12% (due to increasing risk). The Initial capital is $140,000 due to the extra $30,000 capitalized at the end of year zero. The profit figure in Table 6 is Revenue minus OPEX minus the interest payments for the year (all discounted). Please refer to Appendix D for details on the interest payments of the loan. The MVA obtained after five years is also close to $30,000. The previous two cases fail to include depreciation deductions. Assets are usually depreciated over their lifetime and this generates a tax deductible amount each year over the lifetime period. Nonetheless, this usually involves a lot of details and would not serve the purposes of this example. Thus, it is neglected.

Both MVA values are practically the same. But which option is better? If one only has the option to either go for the investment now or not do anything for the next five years, the investment option seems more appealing. This is due to the EVA tendency. The investment option has a higher EVA value that has only slightly began to decrease after peaking. The non-investment option has a clearly declining EVA.

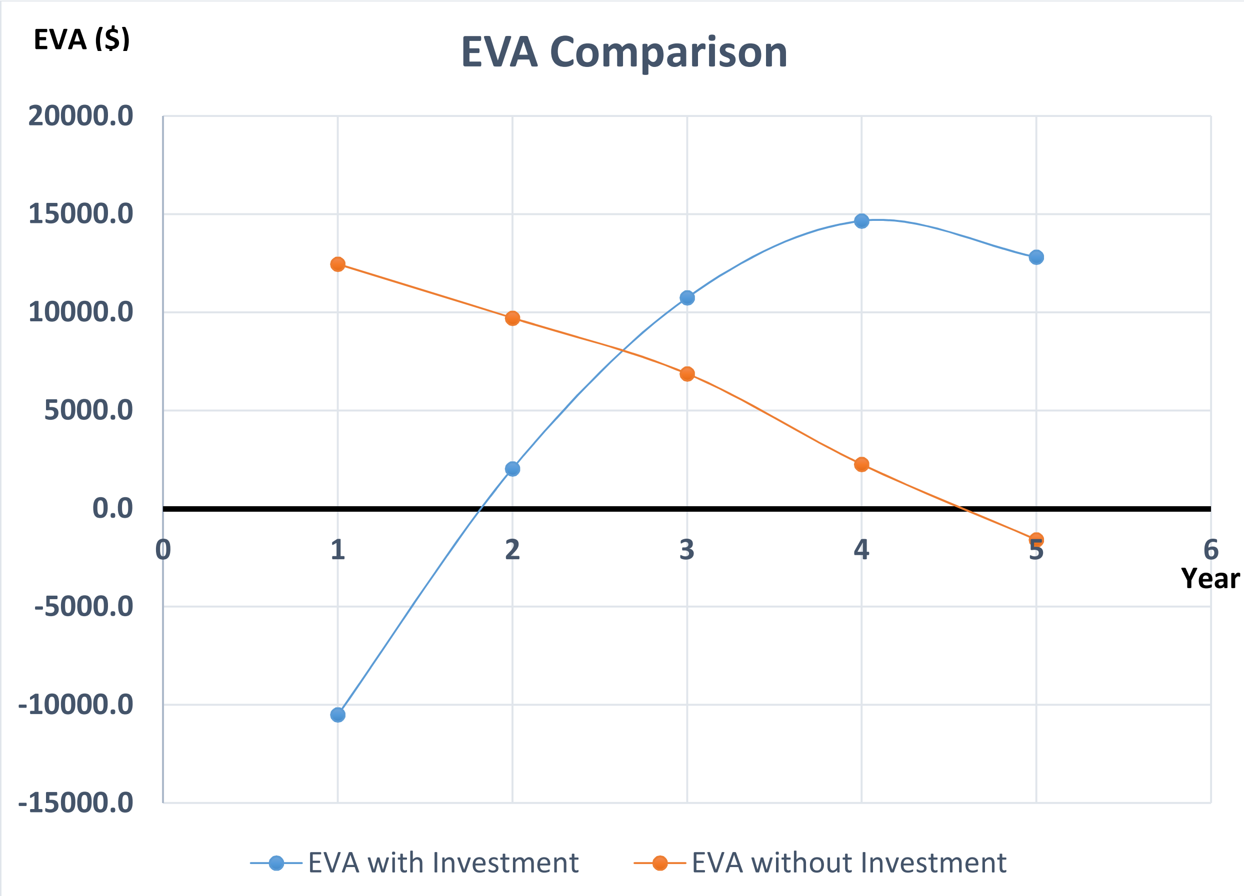


Figure 14: Example V EVA comparison with/without investment

Of course this is too much of a simplistic approach. In reality, if one really wants to avoid taking the investment risk now, one can do so later in time. Preferably, significant action has to be taken before one ends year four and enters five. This is because without action the cashflow ends up being negative for year five. The value of this example is to portray how the use of EVA completely changes the perception a company has of its cashflows. In Table 5, the fifth year shows a negative EVA, but the traditional NOPAT still shows a positive figure of just over five thousand. While in official terms, the company made a profit, if one considers it has almost $70,000 in invested capital and its stockholders expect to get their 10% return, their minimum profit should rather be close to seven thousand. It is understandable that many companies would show resistance to adopt this system since it makes results seem "worse" than a more traditional one. Nonetheless, if this is understood and taken into account, it can make for a much more sustainable approach in the business.

In addition to its already explored benefits, ensuring a high EVA increases the probability of long-term company success. It can be regarded as the key to outperform averages in regards to stock market with the following positive consequences: (Young, 2001)

1) Product and service quality
2) Ability to attract, develop and retain talented people
3) Community and environmental responsibility

The EVA method undoubtedly addresses Gassco's desire to obtain and use a method that reflects the value of replacing an ageing piece of equipment. Nevertheless, EVA is not a tool specifically designed for maintenance. Therefore, it does not have a methodology that indicates how one is supposed to collect and link equipment performance and reliability with its economic metrics.

2.4.3 Asset Utilization (AU)

Another method that is used in the industry in able to determine how effectively one's equipment is being used is "Asset Utilization" (AU). The purpose of this technique is to "…measure the difference between what an asset is capable of producing and what it actually produces…" (Ellis, 1998, p. 2). This difference is usually referred to as the "opportunity gap". It is a measure of the degree to which asset utilization can be improved. (Ellis, 1998)

$$AU = \frac{AO}{MC} * 100 \tag{15}$$

$$OG = MC - AO \tag{16}$$

Where:

- AU: Asset utilization [%]
- AO: Actual output
- MC: Maximum capacity
- OG: Opportunity gap

Date	Maximum Asset Capacity [tons/day]	Actual Output [tons/day]	Asset Utilization [%]	Opportunity Gap [tons]
1-Jan-98	1211	1206	99.6	5
2-Jan-98	1211	1204	99.4	7
3-Jan-98	1211	1199	99.0	12
4-Jan-98	1211	898	74.2	313
5-Jan-98	1211	1188	98.1	23
			Total	360

Table 7: AU & OG Illustration (Ellis, 1998, p. 3)

Table 7 depicts the AU and OG for five different days at a manufacturing plant. This information by itself is not very useful, however. Although one knows January 4th was the day with the least AU and largest OG, one needs to explore what the causes for this are and the impact they have in the company's finances.

In able to give OG a financial meaning, one can calculate the profit one makes out of every unit potentially lost in this gap. This can be then used in the following form:

$$LPO = OG * PPU \tag{17}$$

Where:

- LPO: Lost profit opportunity
- OG: Opportunity gap
- PPU: Profit per unit

For example, according to (17), for January 4th in Table 7 if PPU = $2/ton:

LPO = 313*2 = **$626**

It is great to know how much has been lost due to not utilizing assets to their maximum, nonetheless, the real objective is to find out why this is happening and how it can be avoided. The AU method calls to divide losses into several categories in able to pin point potential areas of focus. (Ellis, 1998)

- Equipment type
- Equipment system
- General cause

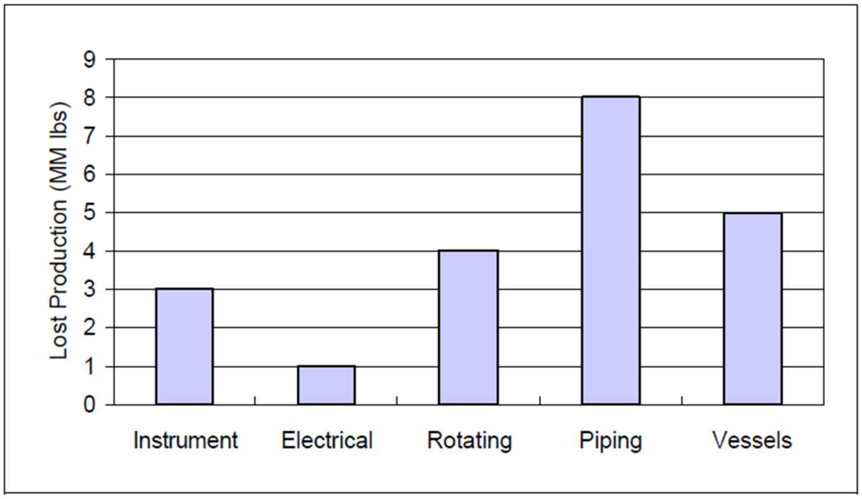


Figure 15: Lost production by equipment type

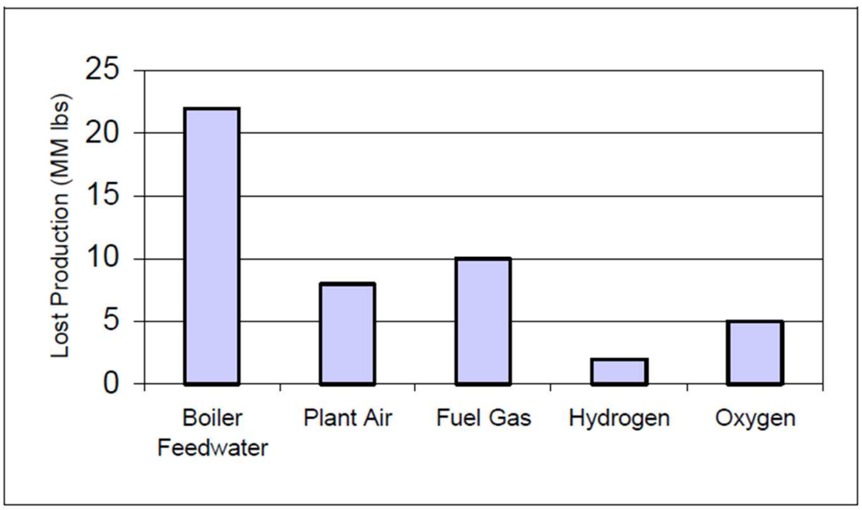


Figure 16: Lost production by equipment system

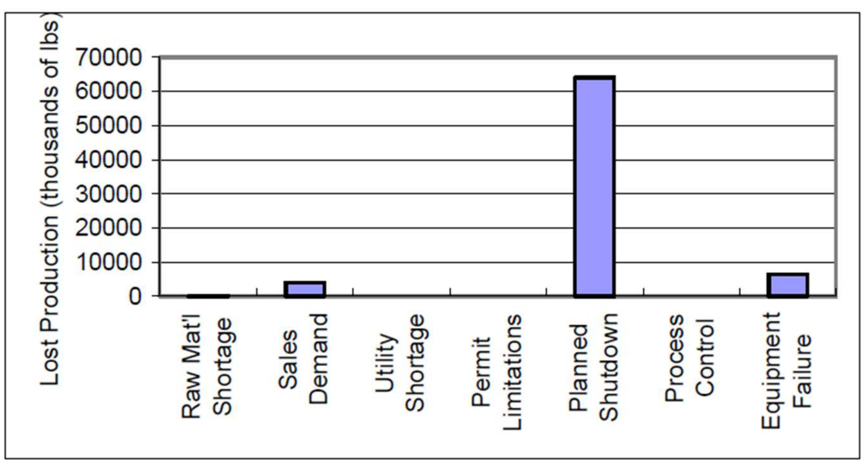


Figure 17: Lost production by general cause

Figure 15, Figure 16 & Figure 17 exemplify how losses can be categorized and graphed against each other in able to identify the largest areas of improvement opportunity. From them, one can rapidly see the piping system, boiler feed and planned shutdowns require special focus.

The AU method is a simple approach to quickly realize if one's assets (equipment) are being used properly (close to their maximum capacity). It is tempting to try to simply maximize the MTTF on as many pieces of equipment as possible. Nevertheless, this might not be the best way to reduce losses. One must identify the sources of such and act accordingly. There are cases where the downtime for supposed "improvements" has higher losses than the benefits it creates afterwards. This method is a good alternative for a healthy cooperation between general management and maintenance management teams. It can help them both see eye to eye on what to prioritize.

2.4.4 Cost of Unreliability (CoUr)

One methodology, tailored specifically for maintenance decision-making, is called "Cost of Unreliability" (CoUr). This method follows a process that ultimately determines how much money is spent (lost) due to the unreliabilities present in a system. Unreliability causes equipment and process failures, which ultimately waste money. The method divides costs arising from unreliabilities in several groups. (Vicente, 2012)

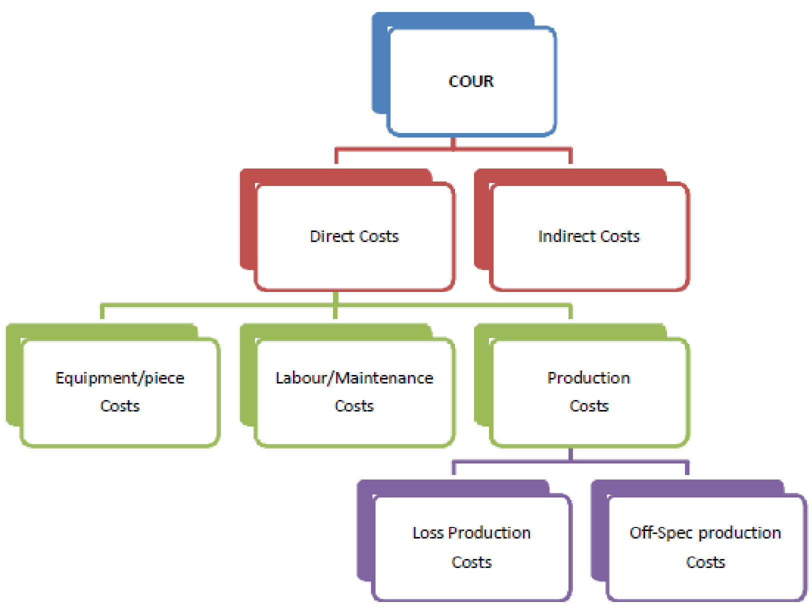


Figure 18: CoUr subdivision of costs (Vicente, 2012)

$$\text{CoUr} = \text{Dc} + \text{Ic} \tag{18}$$

Where:

- CoUr – Cost of unreliability
- Dc – Direct costs (of unreliability)

- Ic – Indirect costs (of unreliability)

$$Dc = Ec + Lc + Pc \tag{19}$$

Where:

- Dc – Direct costs (of unreliability)
- Ec – Equipment spare costs (of unreliability)
- Lc – Maintenance related labor costs (of unreliability)
- Pc – Production costs (of unreliability)

Combining (18) & (19):

$$CoUr = Ec + Lc + Pc + Ic \tag{20}$$

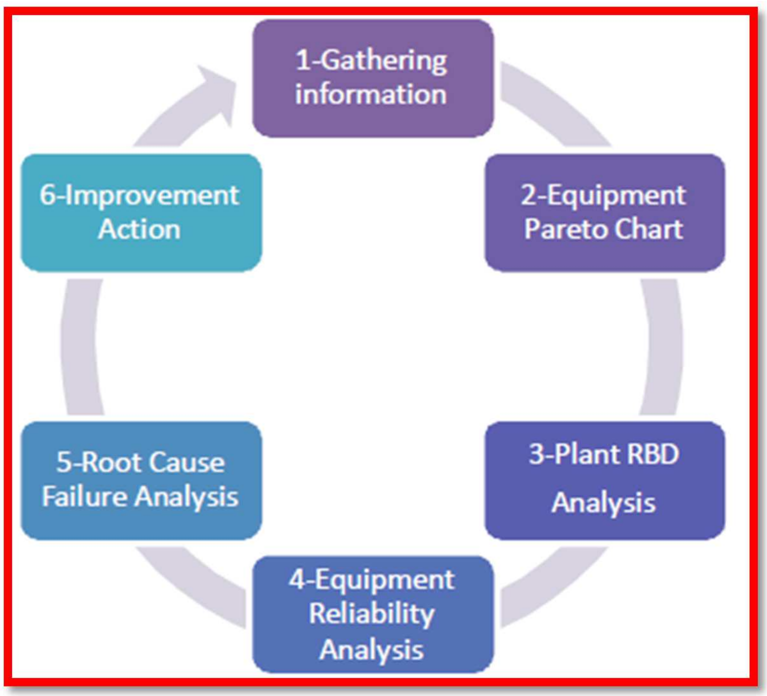


Figure 19: CoUr methodology (Vicente, 2012)

Figure 19 shows the overall process that needs to be followed to obtain CoUr.

1. Broad general information on the system to be analyzed is gathered. No specific data on reliability is required yet. However, for initial comparison reasons, general numbers on maintenance expenses and production losses divided by subsystem have to be obtained.
2. At this point, the information in the previous step is analyzed to determine which subsystems are the ones with the highest potential CoUr. From this point on, focus shall be on these areas.

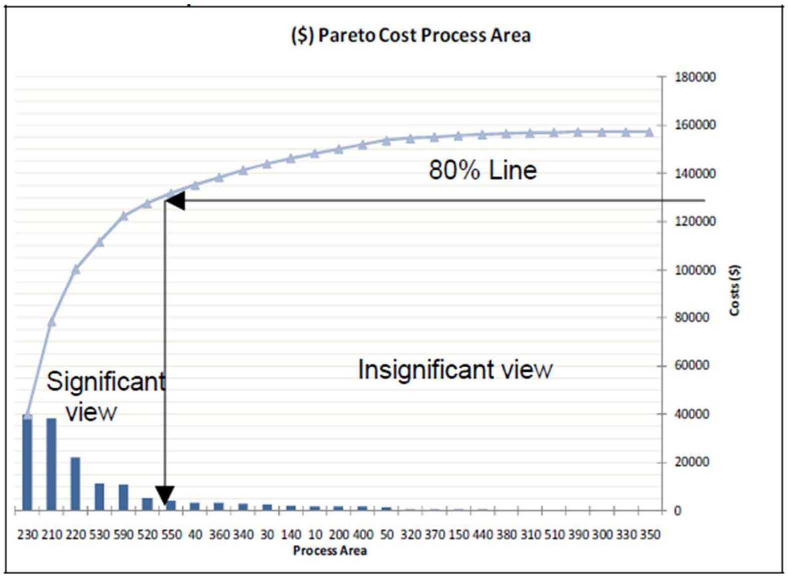


Figure 20: CoUr Pareto cost per process area (Vicente, 2012)

Figure 20 shows process areas in the horizontal axis. That means that for example, area 230 is the mixing system, 210 is the pumping one and 350 the storage area. The vertical axis shows costs associated to production loss due to equipment failure as well as maintenance costs regarding labor and spares required for repair. The Pareto principle states that roughly 80% of the effects come from 20% of the causes. It is therefore that Figure 20 traces an 80% line on the y axis until it intersects the cumulative cost line and then considers only the process areas that are to the left of it. Focusing on these areas has a greater immediate impact with much less effort. (Vicente, 2012)

3. After the areas of focus have been identified, RBDs on the subsystems to be analyzed shall be elaborated.

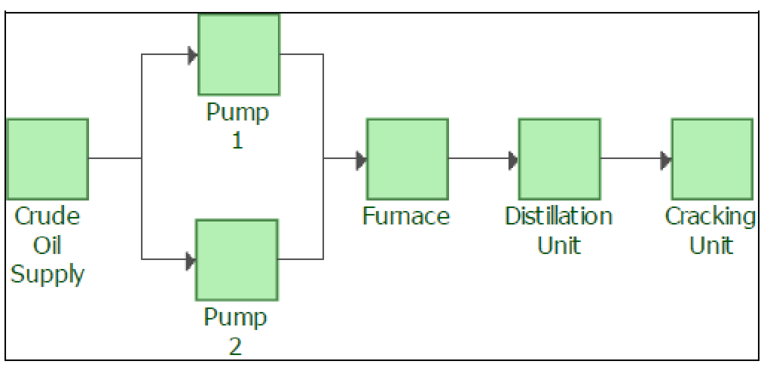


Figure 21: RBD for CoUr example (Vicente, 2012)

In able to properly build RBDs, the interdependencies between components must be well understood. In able to do so, one must follow the methodology previously described on 2.3.3.

4. Once there are RBDs on the systems of interest. Perform an equipment reliability analysis that ends up with technical data translated into financial losses.

At this time, reliability data shall be collected and input in the RBDs. Numerical calculations for the RBDs shall be done analogous to the ones presented in Example II. These shall later be translated to financial values. RBDs will be able to output MTBF, and downtime if MTTR & failure rate are known and the procedure on Example II is followed. With such output from RBDs and some additional information, a table like the following shall be constructed.

DATA	Deshydratation		Recovery NGL		Compression	Summary
Study Interval (hrs)	87.600,00		87.600,00		87.600,00	8.760,00
# of Failures	1,00		2,00		3,00	0,60
MTBF	87.600,00		43.800,00		29.200,00	14.600,00
Failure Rate	1,142E-05	+	2,283E-05	+	3,425E-05	6,85E-05
Failure per year	0,10	+	0,20	+	0,30	0,60
MTTR(hrs/fail)	8,00		25,00		12,00	15,67
Downtime (hrs/year)	0,80	+	5,00	+	3,60	9,40
Production Lost ($)	36.000,00	+	225.000,00	+	162.000,00	423.000,00
Mainenance Cost ($)	50.800,00	+	27.500,00	+	13.200,00	91.500,00
COUR($)	86.800,00		252.500,00		175.200,00	**$ 514.500,00**

Table 8: CoUr summary table (Vicente, 2012)

The study interval in Table 8 is of ten years (87,600 hours). However, the CoUr figures are later standardized to a yearly basis once failures are accommodated on a "per year" form. Production lost (Pc) can be calculated by finding out how much money is lost per hour of downtime and performing a simple multiplication. Analogous to this, maintenance costs (Ec + Lc) can be found by estimating an average cost to repair a failure and then multiplying this by the number of yearly failures.

5. Identify the root cause of the problems by analyzing interdependencies as well as failure modes and mechanisms.

At this stage, the losses due to unreliabilities have already been determined. Sometimes, looking at the RBDs with numbers can quickly point to interdependency issues that could easily be resolved with redundancy or parallel trains. However, there are times where certain components simply have to perform better in able to cut on the current losses. At this point, replacement scenarios clearly come into play, nonetheless, replacing something without finding out why it failed in the first place is a recipe for continuous loss. Like stated in 2.3.1, the use of an FMECA could be helpful in identifying failure modes and mechanisms.

6. Elaborate a plan of action to improve the current situation (decrease CoUr).

After going through the first five steps of the CoUr methodology, the final objective is to come up with a clear course of action that will ensure a reduction in CoUr. This does not necessarily mean that an exact strategy will be known; which components to change, which to install monitoring on, etc. It does mean, however, that specific goals on which ones need to be further investigated are required. At this point, the people involved must also be made aware of the possible options available. It is also imperative that tasks are assigned to individuals and that they are held accountable for them. Maintenance management policies may also change or at least be put under evaluation after having carried out this process. (Vicente, 2012) (Bradley & Dawson, 1998)

It is more than clear that the CoUr analysis can significantly aid a company in reducing its equipment failure related losses. It is extremely intuitive, the concept can be easily grasped by anyone. Nonetheless, it seems to be somewhat limited in financial terms since it does not really involve any calculations that focus on the bottom line performance of the firm (unlike EVA).

3 Project Challenges

After completing the literary survey, it is evident that there are several interesting options that have already been developed in the past and could aid Gassco with some of their equipment replacement dilemmas. While simple DCF methodologies like NPV are in use, it still seems like there are some equipment-replacement decisions being taken merely due to compliance requirements. Even if usually there is no way around these scenarios, especially if the requirements are external, it is extremely frustrating to have to go through with them with no real financial incentive. Moreover, certain regulations allow deviations as long as a thorough analysis is made showing that a better alternative is indeed available.

Gassco AS has recently gone through a series of replacement evaluation analyses for several of their systems. In several cases, the decision was made to replace obsolete equipment due to compliance requirements. In others, there was a financial driver identified through DCF techniques. Nonetheless, in others, it seemed like the replacement option had no clear economic justification. It is under this context that a better alternative shall be sought.

3.1 Reflecting a Financial Business Driver for Equipment Replacement

The DCF concept has one clear objective, to assist in making financial decisions pertaining possible investments. It is great at accomplishing that with investments that result in the expectation of direct additional revenue. But, how can they be used when the "investment" that shall be made will not result in any revenue, but rather will "avoid" the loss of it? Such is the case with equipment-replacement. Huge investments might be made and one can still be sure of one thing, if the ultimate production rate of a plant remains the same, such investment will not have a direct financial benefit for the company. Under such circumstances, it is extremely difficult to support the majority of these replacements. Maybe, rightfully so, maybe wrongly. It is therefore that usually both internal and external regulations exist in this regard, to make sure one is "on the safe side" of things for the most part. But even then, is it not possible to end with the frustration that arises from simply taking decisions to fulfill a regulation?

This project has to be able to provide a more substantial approach on how to determine if there is enough of a financial driver to make an equipment replacement call. The results might end up bringing more disappointment as one realizes how conservative regulations can be. Nonetheless, a better decision-support methodology is needed.

3.2 Developing a General Methodology

All economical and financial models are fairly easy to adjust to just about any firm. The numbers can vary greatly, but the procedure that must be followed and its sub-steps will rarely change. Although this is true for any DCF methodology, including all of the ones explored previously in section 2.4, it fails to hold when dealing with reliability engineering. The steps are also all the same, but some of the details and sub-steps vary tremendously.

Even the same type of plants with similar output products and maximum capacities will have extreme differences in reliability metrics. RBDs and FTAs are system dependent and thus have to be custom made every single time. Moreover, even if two systems of similar plants in different parts of the world have can be modelled with the exact same RBD or FTA, their failure rate data can never be the same. Even if all equipment and connections were from the same manufacturers and were just as old. This is because failure rate depends on very many factors, ranging from hours of use, climate conditions, preventive maintenance practices, operation practices, etc. It is therefore usually accepted that the step of a methodology that deals with reliability will by no means be general and will require specific analysis. Shall this be accepted, or can something be done to "generalize" this step?

RBDs and FTAs are made up of components, one cannot generalize something that is built with particular components. In able to even begin to attempt this, the building blocks of these entities require a general nature. While items are not general, their failure modes, causes and modules are fairly general. There might be a chance of using these concepts to build more general diagrams and trees. It remains to be seen if this is possible and even then, if it makes the process any easier. Nevertheless, this will be explored and carried out if feasible.

3.3 Linking Financial Metrics to Technical Tools

The CoUr methodology appears to be able to go from a technical setting into financial metrics seamlessly. It includes failure data through the development of RBDs and transitions into production loss (Pc) and maintenance repair costs (Ec + Lc) smoothly. Would it be sufficient, however, to simply use this methodology and try to use it as an absolute reference for equipment-replacement decisions? If so, would one simply compare the expected CoUr right after replacement with the one right before it and replace if CoUr goes down? This does not emerge as a good enough solution. It would simply imply any measures that can lower CoUr shall be taken no matter the cost. The investment required cannot be disregarded, nor can any additional benefits or hindrances to cashflows resulting from a replacement acceptance.

The AU concept seems to be inherently included in the CoUr methodology as illustrated in step 2 of 2.4.4 and through Figure 20. While CoUr, does not give out the percentage of the total assets that is being utilized, it tries to increase this figure in the same way as the AU approach does; identify the areas of larger "opportunity gap" and solve them. CoUr focuses usually on "system areas" because this makes it easier afterwards to develop RBDs relating equipment and components with interdependencies. The equipment type and general cause paths could not easily transition into the reliability scenario.

A simple NPV with CoUr combination could work well. The difference in CoUr could be reflected in the yearly cashflows through decreased expenses. Any additional benefits can be input as increases in revenue. One can also extend the period of examination in the future to recover the investment and thus get a clearer picture of the alternatives. Even so, how is this any different from a normal NPV practice? It appears that the clear cut, intuitive value of CoUr would be loss in between cashflows. If there is one thing that is clear so far is that if this value of CoUr can somehow be used, it would be of extreme importance.

Out of the explored, the EVA method is perhaps the likeliest to get a company into a sustainable success road if followed properly. It is extremely interesting and generates a shift in the perception of what a firm must actually seek in able to prosper. It changes the old-fashion ideal that sees expenses like personnel training as ones of hardly quantifiable value. It also puts a firm in a much tighter cashflow situation by demanding it to consider that ultimately, all of its invested capital has got to return its stockholders their expected return. This forces organizations to handle their spending more carefully and to see all of it as an investment that must pay off. Although its value is undeniable, it unfortunately has no direct way of handling the technical aspects of maintenance management. It was not even thought of for maintenance, much less for equipment replacement because these assets are always capitalized anyways.

EVA and CoUr are clearly the two methods that could give the most value to Gassco if they could somehow be combined. This is a possibility that has to at least be explored. There is no guarantee that this will emerge as a fruitful attempt, but it is well worth the try.

3.4 Obtaining Data

One of the more restrictive areas of any study is related to the collection of data. It is counterintuitive to think this can be such a great limitation when we had never been as good at measuring things. Not only can we do so in real time, but such information can be easily stored for posterity. The data problem has shifted from "not enough" into "too much". Some time ago there just was not enough capacity to gather all information required. Now, there is a lot of information, but it has to be properly processed for it to have any worth. Some of it is useless and has to be discarded, while other parts have to be interrelated.

Looking into the past is a good reference for what might be expected in the future. Reliability data is usually obtained from historic failure cases. In equipment replacement scenarios, however, there is also a need to look into the future. The ability to compare the current circumstances with the ones expected after replacement has to be available. This look into the future can be less straight forward and its uncertainties much higher. A model is only as good as the data it uses, thus this part shall not be undermined.

At times, the processes used for decision-making support are oversimplified due to the lack of appropriate data available. This is an obvious consequence of such circumstances, but it also hinders the improvement potential of a company. If one develops more robust methodologies, their end result might be that there is not enough data for it to be carried out, however, it might also incentivize the organization to find out a way to ultimately obtain this information in the future. This project must try to keep that in mind and avoid too many oversimplifications on the back of this possibility.

3.5 Developing a "User-Friendly" Model

Any process is useless unless it can be clearly understood and carried out by its final user. This project clearly has the possibility of breaking common paradigms and practices. Nevertheless, the notion that this has to remain easy to use shall be kept. The ultimate model provided by this project shall be easy to grasp and replicable while adding value to the organization. This is not the first time a task like this has been attempted, most of these efforts die early due to their impracticality. Even if their potential benefits might be large, difficulty in implementation is a huge downside.

Not only shall the process be "user friendly", but the manner in which it is presented shall be optimal as well. This project will continue with the use of examples throughout the development phase of its model in able to assist in the understanding of the concept. The use of visual aid (figures, graphs, tables) will be prioritized over long text. Sequences will be presented as numbered steps when applicable.

3.6 Fulfilling the Project's Objective

The main objective can resumed as, to develop a quantitative model that evaluates if an equipment replacement scenario is financially justifiable. The challenges to fulfill this goal can be resumed as:

- Provide direct financial potential gains for the evaluation
- Present a model that can be used for most equipment replacement scenarios
- Produce a methodology that is technically sound but yields financial results
- Develop an alternative without oversimplification due to fearing lack of appropriate data
- Make sure the end-result is understandable and provides value

4 Recommended Methodology Development

Before any real cases Gassco might currently face are explored, an ideal methodology is expected to be developed. While this might mean that its application will be more of a challenge, it is also a possibility to produce something that can yield a "best case scenario". It also allows the project to take a "forward thinking" and creative approach without worrying about practical restraints for the time being. Even so, the guidelines shown in 3.6 are to be followed. This chapter presents the details followed to obtain an ideal methodology that will attempt to suit the project's objective.

Considering the analysis made in 3.3, an attempt to combine EVA and CoUr shall be made. In theory a model that combined these two would be able to bring the long term robust economic-type benefits of EVA together with the technically sound features and perceptibly prompt gains of CoUr.

4.1 Equation and Inequality Deduction

In an equipment replacement scenario, a comparison between two possibilities has to be made: replacement vs non-replacement. According to 2.4.2, EVA's ultimate goal is to maximize the sum of the present value of its future cashflows. This is described by (14)

$$MVA = \sum_{i=1}^{n} R_i - \sum_{i=1}^{n} OPEX_i - \sum_{i=1}^{n} T_i - \sum_{i=1}^{n} (IC_i * CoC_i)$$

(14) Can then be used to compare the two scenarios and determine if replacement makes sense financially.

$$\Delta MVA = MVA_R - MVA_N \tag{21}$$

Where:

- MVA_R: Market value added with replacement
- MVA_N: Market value added with no replacement
- ΔMVA: Market value added net difference

MVA_R has to be larger than MVA_N for a replacement scenario to be of financial worth. Thus, (21) shall fulfil the following inequality:

$$MVA_R - MVA_N > 0$$

From this moment on, the following sub-indexes will apply to all variables in any equation:

- R: when a decision has been made to replace the current equipment
- N: when a decision has been made to NOT replace the current equipment
- x: applicable for any of the previous two

In the following deductions, variables inside sums will not have the sub-index "i", but this will be implied.

(21) Can then be extended by combining it with (14) and using the "R" and "N" sub-indexes:

$$\Delta MVA = \sum_{i=1}^{n}[R_R - R_N] - \sum_{i=1}^{n}[OPEX_R - OPEX_N] - \sum_{i=1}^{n}[T_R - T_N] - \sum_{i=1}^{n}[(IC_R * CoC_R) - (IC_N * CoC_N)]$$

Every sum operator of this extended version will now be analyzed individually, thus:

$$REV = \sum_{i=1}^{n}[R_R - R_N] \tag{22}$$

$$EXP = \sum_{i=1}^{n}[OPEX_R - OPEX_N] \tag{23}$$

$$TAX = \sum_{i=1}^{n}[T_R - T_N] \tag{24}$$

$$CAP = \sum_{i=1}^{n}[(IC_R * CoC_R) - (IC_N * CoC_N)] \tag{25}$$

Thus:

(21) = (22) + (23) + (24) + (25)

$$\Delta MVA = REV - EXP - TAX - CAP$$

(22) Will be analyzed first. This will be done keeping in mind that the objective is to include (20):

$$\text{CoUr} = \text{Ec} + \text{Lc} + \text{Pc} + \text{Ic}$$

Pc can be linked to revenue, since it represents production loss costs of unreliability. If an equipment replacement is made, the revenue is expected to increase. Revenue for any case can be divided as follows:

$$R_x = R^* - Pc_x$$

Where:

- R_x: Actual revenue for any scenario
- R*: Maximum attainable revenue
- Pc_x: Production loss cost of unreliability for any scenario

Thus:

$$R_R = R^* - Pc_R$$

$$R_N = R^* - Pc_N$$

(22) Can then be written as:

$$REV = \sum_{i=1}^{n} [(R^* - Pc_R) - (R^* - Pc_N)] = -\sum_{i=1}^{n} [Pc_R - Pc_N]$$

Analogous to (21):

$$\Delta X = X_R - X_N$$

Where:

- X_R: "X" variable with replacement
- X_N: "X" with no replacement
- ΔX: "X" net difference

This means "X" can take the form of any variable, thus (22):

$$REV = -\sum_{i=1}^{n} \Delta Pc$$

(23) Will be next in the analysis.

$$EXP = \sum_{i=1}^{n} [OPEX_R - OPEX_N]$$

Ec and Lc can be linked to OPEX, since they represent maintenance loss costs of unreliability. If an equipment replacement is made, the OPEX can either increase or decrease. OPEX for any case can be divided as follows:

$$OPEX_x = OPEX^* + Ec_x + Lc_x + Vc_x$$

Where:

- $OPEX_x$: Actual OPEX for any scenario
- OPEX*: Minimum attainable OPEX

- Ec_x: Spare part cost of unreliability for any scenario (only for breakdowns)
- Lc_x: Repair labor cost of unreliability for any scenario (only for breakdowns)
- Vc_x: Variable OPEX for any scenario

Vc_x is introduced in able to compensate for operational costs that might change after replacement but that are not linked to Ec nor Lc (e.g. less energy consumption by the new equipment). It is important to keep in mind it will include regular maintenance expenditure (planned) that is not linked to breakdown.

Thus:

$$OPEX_R = OPEX^* + Ec_R + Lc_R + Vc_R$$

$$OPEX_N = OPEX^* + Ec_N + Lc_N + Vc_N$$

(23) Can then be written as:

$$EXP = \sum_{i=1}^{n} [(OPEX^* + Ec_R + Lc_R + Vc_R) - (OPEX^* + Ec_N + Lc_N + Vc_N)]$$

$$EXP = \sum_{i=1}^{n} [(Ec_R + Lc_R + Vc_R) - (Ec_N + Lc_N + Vc_N)]$$

Furthermore, (23) can be condensed into:

$$EXP = \sum_{i=1}^{n} [\Delta Ec + \Delta Lc + \Delta Vc]$$

However, a very important part of the EVA flow is missing. If a replacement is to be made, a large negative flow will be present on the first year to represent the investment one incurred on. This is a one-time expense and will therefore be outside the sum operator. Finally, (23) becomes:

$$EXP = IC_R + \sum_{i=1}^{n} [\Delta Ec + \Delta Lc + \Delta Vc]$$

Next, (24) will be broken down.

$$TAX = \sum_{i=1}^{n} [T_R - T_N]$$

Tax can actually be expressed as a function of the other variables in (21) since:

$$T_x = TR * (R_x - OPEX_x)$$

Using the previous equivalences:

$$\Delta T = T_R - T_N = TR * [(R_R - R_N) - (OPEX_R - OPEX_N)]$$

$$\Delta T = TR * (-\Delta Pc - \Delta Ec - \Delta Lc - \Delta Vc)$$

Where:

- TR: Tax rate

Depreciation has to be taken into account somehow, and this is dependent on IC.

$$\Delta IC = IC_R - IC_N$$

If it is assumed that a non-replacement scenario yields obsolete equipment, it would mean such equipment has already been fully depreciated and IC_N is zero, thus:

$$\Delta IC = IC_R$$

It will also be assumed that the invested capital required for the replacement would be depreciated uniformly along its lifetime, thus the depreciated quantity for every period would be:

$$Yearly\ Depreciation = \frac{IC_R}{n}$$

The yearly depreciation is constant. For this to be input into the general formula, it also means that the analysis is only valid when considered for "n" years in which the replacement case does not need further investment and the non-replacement one fails to do any. Also considering the tax rate to be constant, (24) becomes:

$$TAX = \sum_{i=1}^{n}[\Delta T] = TR * \sum_{i=1}^{n}[(-\Delta Pc - \Delta Ec - \Delta Lc - \Delta Vc) - TR * \sum_{i=1}^{n}[(\frac{IC_R}{n})]$$

Finally, (25) will be explored. Remembering IC_N is zero:

$$CAP = \sum_{i=1}^{n}[(IC_R * CoC_R)]$$

Normally, CoC would not change in the explored period, therefore it will be considered constant, yielding:

$$CAP = CoC * \sum_{i=1}^{n}[(IC_R)]$$

The sum of IC_R from the first year into the last can be simplified due to the fact that depreciation is uniform all the way into the last year.

$$CAP = CoC * [\left(IC_R - \frac{IC_R}{n}\right) + \left(IC_R - \frac{2 * IC_R}{n}\right) + \left(IC_R - \frac{3 * IC_R}{n}\right) ... + \left(IC_R - \frac{n * IC_R}{n}\right)]$$

$$CAP = CoC * \left[(n * IC_R) - \frac{IC_R}{n} * (1 + 2 + 3 ... + n)\right]$$

$$CAP = CoC * \left[(n * IC_R) - \frac{IC_R}{n} * \left(\frac{(n+1) * n}{2}\right)\right]$$

$$CAP = CoC * [IC_R * (n - \left(\frac{(n+1)}{2}\right)]$$

$$CAP = [CoC * IC_R \left(\frac{(n-1)}{2}\right)]$$

After all these deductions, (21) becomes:

$$\Delta MVA = REV - EXP - TAX - CAP$$

$$\Delta MVA = -\sum_{i=1}^{n} \Delta Pc - IC_R - \sum_{i=1}^{n} [\Delta Ec + \Delta Lc + \Delta Vc] - TR * \sum_{i=1}^{n} [(-\Delta Pc - \Delta Ec - \Delta Lc - \Delta Vc - \frac{IC_R}{n})] - [CoC * IC_R \left(\frac{(n-1)}{2}\right)] > 0$$

If the Δ's are considered to be the same for every year along the examination period, then the previous expression can turn into:

$$\Delta MVA = -n * [\Delta Pc] - IC_R - n * [\Delta Ec + \Delta Lc + \Delta Vc] - n * [TR * (-\Delta Pc - \Delta Ec - \Delta Lc - \Delta Vc)] + TR * \sum_{i=1}^{n} \left[\frac{IC_R}{n}\right] - \left[CoC * IC_R \left(\frac{(n-1)}{2}\right)\right] > 0$$

Rearranging the terms:

$$\Delta MVA = -n * [\Delta Pc] - n * [\Delta Ec + \Delta Lc + \Delta Vc] - n * [TR * (-\Delta Pc - \Delta Ec - \Delta Lc - \Delta Vc) - IC_R + [TR * IC_R] - \left[CoC * IC_R \left(\frac{(n-1)}{2}\right)\right] > 0$$

Having the whole inequality as a product of "n":

$$\Delta MVA = n * \left\{ [-\Delta Pc] + [-\Delta Ec - \Delta Lc - \Delta Vc] + [TR * (\Delta Pc + \Delta Ec + \Delta Lc + \Delta Vc)] - \left[\frac{IC_R}{n}\right] + \left[\frac{TR}{n} * IC_R\right] - \left[\frac{CoC * IC_R}{n} * \left(\frac{(n-1)}{2}\right)\right]\right\} > 0$$

Dividing both sides by "n" (right hand side remains zero) and rearranging:

$$\Delta MVA = [(\Delta Pc + \Delta Ec + \Delta Lc + \Delta Vc) * (TR - 1)] - \left[\frac{IC_R}{n}\right] + \left[\frac{TR}{n} * IC_R\right] - \left[\frac{CoC * IC_R}{n} * \left(\frac{(n-1)}{2}\right)\right] > 0$$

$$\Delta MVA = [(\Delta Pc + \Delta Ec + \Delta Lc + \Delta Vc) * (TR - 1)] + \left[\frac{IC_R}{n}\right] * \left[TR - CoC * \left(\frac{n-1}{2}\right) - 1\right] > 0$$

Next, the terms linked to investment and taxes are placed on the right hand side of the inequality. (TR-1) will always be negative, since the maximum value of TR is 1. Thus the inequality sign is flipped in the next step after division by a negative number:

$$[(\Delta Pc + \Delta Ec + \Delta Lc + \Delta Vc)] < \frac{\left[\frac{IC_R}{n}\right] * \left[1 + CoC * \left(\frac{n-1}{2}\right) - TR\right]}{(TR - 1)} \quad (26)$$

(26) Is a reference inequality. It helps determine if a replacement investment of ageing equipment should take place. Financial justification exists only under conditions under which the inequality is fulfilled. The variable costs on the left hand side are of particular interest since they include non-technical aspects of costs that can either rise or fall after replacement. For example, it can include higher or lower costs arising from a difference in energy consumption. This is also where loan interest payments would be placed. It is also this variable that shall encompass any other costs that can affect the investment decision (e.g. indirect costs of unreliability). In an attempt to make this parameter more accurate:

$$\Delta Vc = \Delta Oc + \Delta Fc + \Delta Rc$$

Where:

- ΔOc: Overly costs; reducible/increasable costs linked to the equipment (e.g. energy consumption, staff requirement, operational planned maintenance)
- ΔFc: Financial costs (e.g. loan interest payments)
- ΔRc: Reactive costs (e.g. emergency spending, penalties)

(26) Then can be expressed as:

$$[(\Delta Pc + \Delta Ec + \Delta Lc + \Delta Oc + \Delta Fc + \Delta Rc)] < \frac{\left[\frac{IC_R}{n}\right] * \left[1 + CoC * \left(\frac{n-1}{2}\right) - TR\right]}{(TR - 1)}$$

However, the above expression's right side will always be negative (due to TR always being less than 1). And the left side will have to be even more negative for an investment to be justifiable. In able to have an inequality that is easier to use, the following will be considered:

$$\Delta X = X_R - X_N$$

$$-\Delta X = X_N - X_R = \Delta X'$$

Where:

- ΔX': Difference between non replacement scenario and replacement one. (Valid for any variable)

If both sides are multiplied by (-1), the ΔX' format can be used on the left side, while the denominator on the right side becomes (1-TR). The sign of the inequality has to be flipped and it then becomes:

$$[(\Delta Pc' + \Delta Ec' + \Delta Lc' + \Delta Fc' + \Delta Oc' + \Delta Rc')] > \frac{\left[\frac{IC_R}{n}\right] * \left[1 + CoC * \left(\frac{n-1}{2}\right) - TR\right]}{(1 - TR)} \quad (27)$$

Assumptions for (27)

(27) Is only valid for specific circumstances, thus, a list of the assumptions it considers follows:

1. The sum of the present value of future EVA cashflows of two alternatives is compared
2. The comparison requires "n" years to be selected as the basis for calculations
3. A loan financing choice is assumed with the time to payment equal to "n"
4. The entirety of the investment will be spent on assets and thus capitalized (all can be depreciated, non is required as working capital)
5. The entirety of the investment will be depreciated uniformly until "n"
6. Interests are considered deductible
7. The assets acquired have no salvage value on "n"
8. IC_N is considered to be zero (equipment without replacement is obsolete and already fully depreciated)
9. CoC remains constant for every year
10. TR remains constant for every year
11. ΔX is constant for every year and every variable (in present value, which means, future cash flows would have to rise accordingly)

The strongest assumption is 11. With this, all sum operators can be eliminated and a much simpler expression is obtained, however, it would be surprising to have cases where this would hold. It implies the left hand of the equation either exactly the same with and without replacement or that it changes at exactly the same rate keeping an identical gap at all times. Figure 22& Figure 23 illustrate this, where ΔN's represent non-replacement deltas, and ΔR's represent replacement deltas.

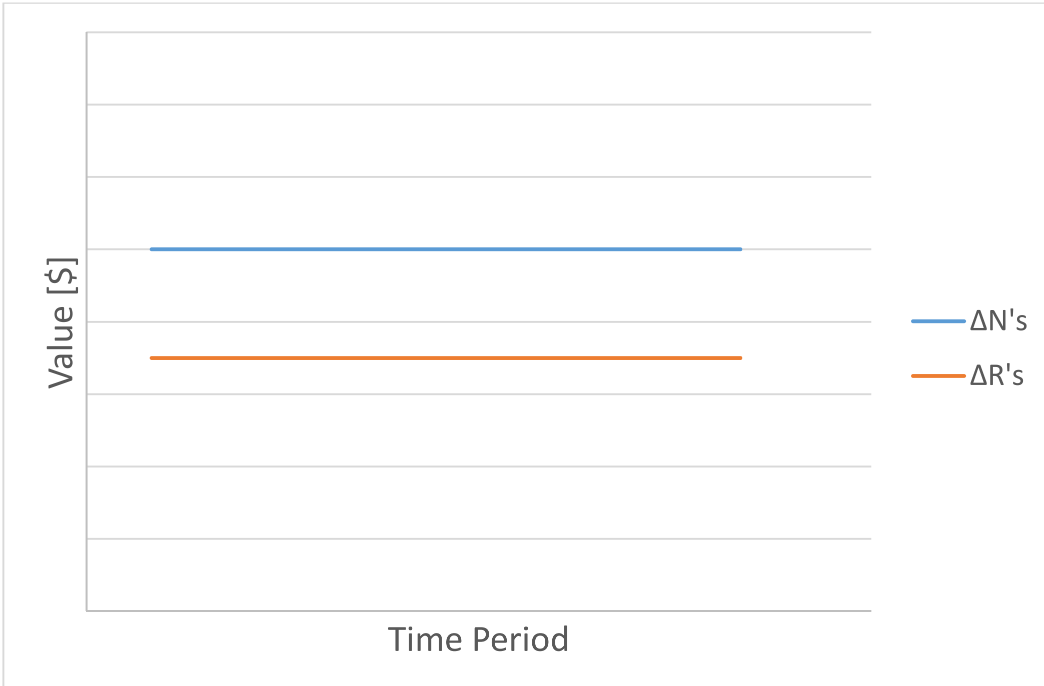


Figure 22: Constant Gap between Unchanged Δ's

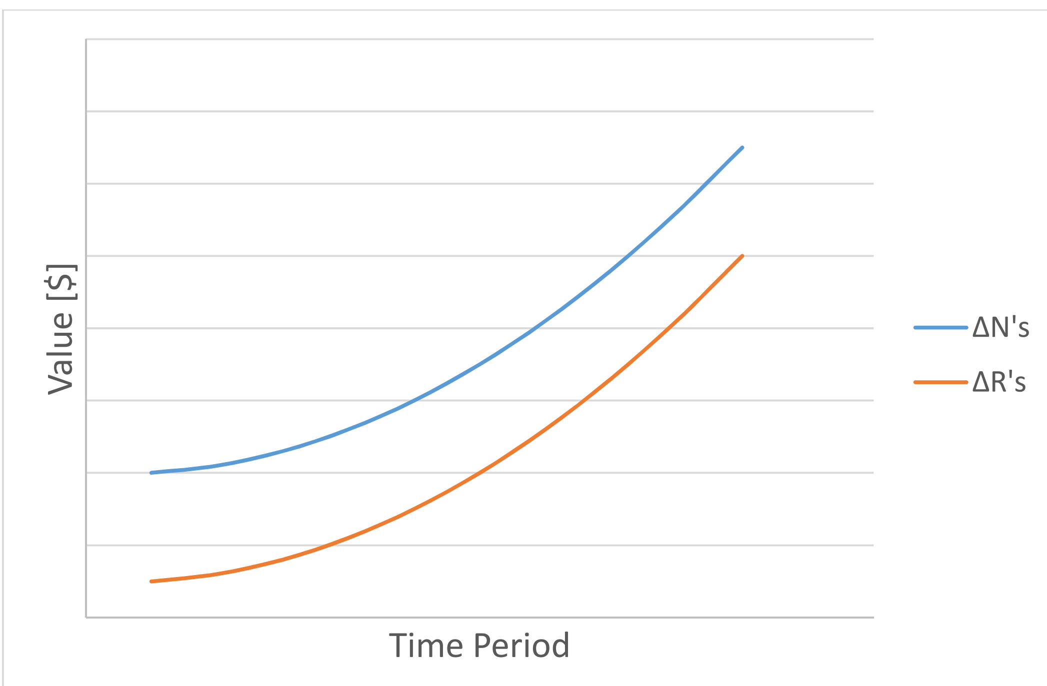


Figure 23: Constant Gap between Changing Δ's

Since the gap between ΔN's and ΔR's is likely to change over the analysis period, the following expression can be used:

$$\sum_{i=1}^{n}[\Delta Pc' + \Delta Ec' + \Delta Lc' + \Delta Fc' + \Delta Oc' + \Delta Rc'] > \frac{[IC_R] * \left[1 + CoC * \left(\frac{n-1}{2}\right) - TR\right]}{(1 - TR)} \tag{28}$$

(28) Is valid for almost the same conditions as (27), however, it does not make the last assumption.

Assumptions for (28)

1. The sum of the present value of future EVA cashflows of two alternatives is compared
2. The comparison requires "n" years to be selected as the basis for calculations
3. A loan financing choice is assumed with the time to payment equal to "n"
4. The entirety of the investment will be spent on assets and thus capitalized (all can be depreciated, non is required as working capital)
5. The entirety of the investment will be depreciated uniformly until "n"
6. Interests are considered deductible
7. The assets acquired have no salvage value on "n"
8. IC_N is considered to be zero (equipment without replacement is obsolete and already fully depreciated)
9. CoC remains constant for every year
10. TR remains constant for every year

Regardless of them being constant or not, the next challenge is to obtain the Δ's.

4.2 Parameter Calculation

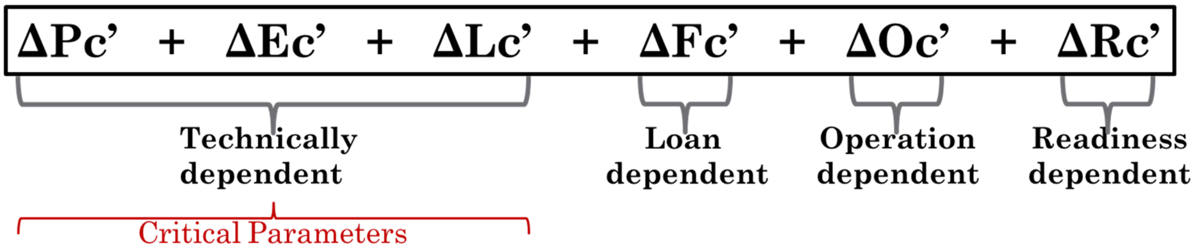
(27) Will be used as a reference, but the analysis made in 4.2 is also valid for (28).

$$[(\Delta Pc' + \Delta Ec' + \Delta Lc' + \Delta Fc' + \Delta Oc' + \Delta Rc')] > \frac{\left[\frac{IC_R}{n}\right] * \left[1 + CoC * \left(\frac{n-1}{2}\right) - TR\right]}{(1 - TR)}$$

There are two sides to these equations. The right hand side has four variables, all of which are straight forward to obtain:

- **IC_R**: Investment required to make the equipment replacement. It can be obtained by getting an estimate from a supplier.
- **n**: Years of analysis. It is recommended to use the number of years until the desired equipment goes obsolete. This also has to be the number of years the loan is taken for.
- **CoC**: Cost of Capital. This can be obtained by looking at the expected return rates of similar companies and one's own.
- **TR**: Tax Rate. This depends on state regulations.

The left side of the inequality is more complicated to obtain, thus a more detailed explanation on how to obtain those parameters will be required.



The non-critical parameters are also quite straight forward. Obtaining them should not be time consuming.

- ΔFc': Financial cost differential. This depends on the interest payments that are required to be made.
- ΔOc': Overly cost differential. This depends on any operational expenses that might change after replacement.
- ΔRc': Reactive cost differential. This depends on changes in unexpected costs like penalties and emergencies.

However, the critical parameters depend on differences in equipment reliability. This is where the CoUr methodology is required and can be linked in able to use (27) or (28). At this point, a traditional approach can be taken as described by Figure 19 in 2.4.4, nonetheless, an attempt will be made to come up with tools to serve as a general guideline. This is to reduce the workload required to obtain these parameters since it is usually very time consuming.

4.3 Obtaining Technical Parameters

Getting these technical parameters would usually involve the use of RBDs and obtaining parameters like MTTR & MTTF to eventually get Pc, Lc and Ec. However, instead of using specific tailored RBDs, general FTAs can be elaborated to be used as guidelines for getting these parameters. Usually FTAs are system dependent ant thus use blocks with components and sub-components. It can however be attempted to use failure modes, effects and mechanisms. These change from case to case, but every system can be connected through them. The other thing that has to be considered is that for this project, a Gas Processing and Transport case is to be considered. The idea will be to generate trees with general dependencies.

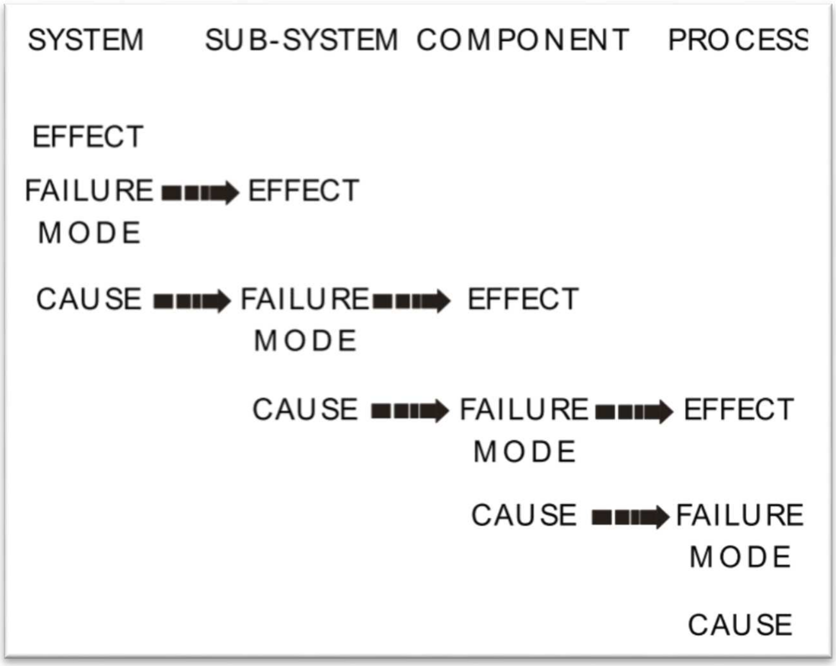


Figure 24: FMEA Cascade Analysis General Concept (Group, 2007)

An FMEA cascade approach can be used. Figure 24 illustrates how this can be done. Each system has an effect, a failure mode and a cause. The sub-systems dependent on the system in turn show an effect due to the failure mode in the system and a failure mode due to the cause.

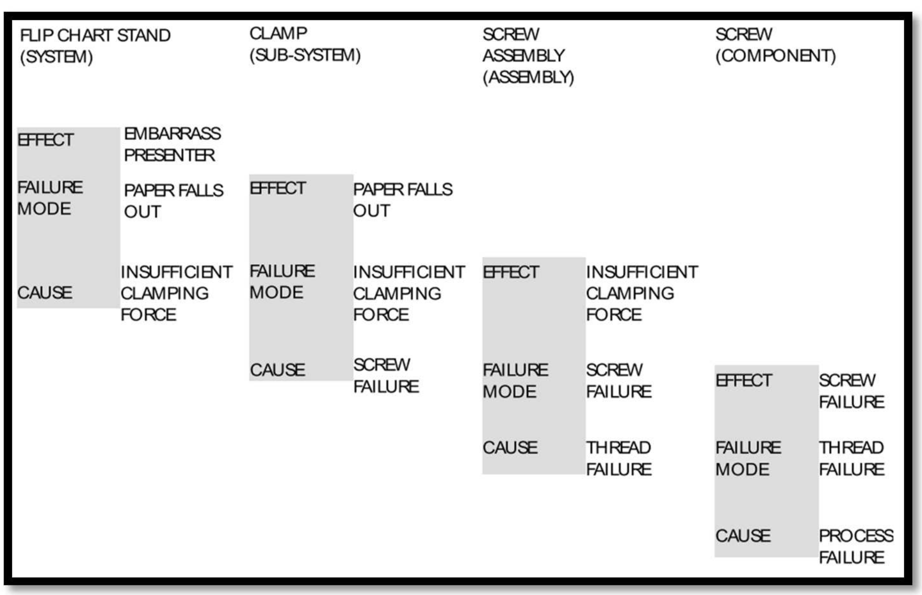


Figure 25: FMEA Cascade Case Illustration (Group, 2007)

Figure 25 show's a specific example using this cascade technique. It goes through the cascade of a situation in which a presenter has a flip chart stand with a paper. The paper is held to the stand with a clamp that is secured by a screw assembly. The cascade explores the potential effect of the presenter being embarrassed by the possibility of the paper falling off the stand due to insufficient clamping force.

The process to elaborate a general FTA would have an analogous approach to Figure 24and Figure 25, however, instead of using a system, subsystem, assembly, component chain, one with circumstances and conditions as well as failure modes, effects, causes and mechanisms will be sought. In able to do this, a good understanding of these failure characteristics is required. The example on Figure 25 is easy to understand, especially when it comes down to causes and effects within the same column (e.g. assembly, sub-system). At the component level, a process failure (cause) leads to a screw failure (effect). Similarly, at the sub-system level, a screw failure (cause) leads to paper falling out (effect). While this is intuitive, FMEAs and thus FTAs include failure modes and mechanisms in able to be systematic and not leave anything out. Humans are quick to look for links between causes and effects and automatically look for solutions. Nonetheless, unless a more disciplined approach is taken, certain things are at risk of being left out. Due to their more complex nature, modes and mechanisms will be further analyzed. (Group, 2007)

4.3.1 Failure Modes

A failure mode is the manner in which an equipment or machinery can fail. It is also sometimes described as the manner by which a failure is observed. In able to determine what the potential failure modes for a particular set are, the analyst has to ask the following question, how could this part, system or process fail? As previously showed on the cascade approach, modes can end up being either effects or causes on other columns (system, sub-system, etc.). (Bloch & Geitner, 2006)

In able to answer the previously stated question, a reference list of potential general failure scenarios can be useful. From (Bloch & Geitner, 2006) the following can be obtained.

Failure Scenario	Details
Incorrect Position	Fails to open, remain or close (complete or partial)
Leakage	Internal or external
Tolerance	Fails out
Output	Erroneous or reduced
Reading (Monitoring)	Loss of
Equipment Status	Start, switch or stop failure
Operation	Premature, delayed, unstable, intermittent

Table 9: Potential general failure scenarios

If for every item in the previous list, one asks the question, how can this happen? Some of the more common failure modes will come up. This is illustrated in Table 10.

2.1 Part/element level
- 2.1.1 Force/stress/impact
  1. Deformation
  2. Fracture
  3. Yielding
  4. Insulation rupture
- 2.1.2 Reactive environment
  1. Corrosion
  2. Rusting
  3. Staining
  4. Cold embrittlement
  5. Corrosion fatigue
  6. Swelling
  7. Softening
- 2.1.3 Thermal
  1. Creep
  2. Cold embrittlement
  3. Insulation breakthrough
  4. Overheating
- 2.1.4 Time
  1. Fatigue
  2. Erosion
  3. Wear
  4. Degradation

2.2 Assembly level
- 2.2.1 Force/stress/impact
  1. Binding
  2. Seizure
  3. Misalignment
  4. Displacement
  5. Loosening
- 2.2.2 Reactive environment
  1. Fretting
  2. Fit corrosion
- 2.2.3 Temperature
  1. Thermal growth/contraction
  2. Thermal misalignment
- 2.2.4 Time
  1. Cycle life attainment
  2. Relative wear
  3. Aging
  4. Degradation
  5. Fouling/contamination
  6. Plugging

Table 10: Some Common Failure Modes (Bloch & Geitner, 2006)

The previous failure modes are general and apply to very many systems in different types of plants and equipment. Depending on the system to be analyzed, these could also be causes and effects across each other.

4.3.2 Failure Mechanisms

As previously shown, failure modes can appear as effects or causes depending on the cascade spot one is on. However, identifying the specific details of the causes of a failure mode can require deeper analysis. Thus, failure mechanisms can be of aid in this regard. A failure mechanism is defined as the detailed description of a technical failure mode. Most are related to physical degradation of components due to operation conditions and other factors like design and material. Mechanisms are very strongly dependent on the types of materials (e.g. plastic, metal) and equipment classification (e.g. electronic, mechanic). (Exprosoft, 2013)

From (Exprosoft, 2013) a list for metal component potential failure mechanisms can be found:

- Corrosion
- Cracking
- Deformation
- Embrittlement

- Fatigue
- Fracture
- Friction
- Wear

Notice how these mechanisms are all already somehow mentioned in Table 10 as failure modes. That is because, while more detailed, mechanisms can still be modes. Nonetheless, these can further be broken down into more detailed mechanisms. For example, corrosion can be further broken down into:

Corrosion Main Cause	Details
Bacteria	Sulfate reducing bacteria
	Iron oxidizing bacteria
Moisture	Environment
	In-process substance
Other gases	H_2S
	CO_2

Table 11: Corrosion failure mechanisms

From (Corp., NA), the following list of failure mechanisms for electronic component failure modes can be developed.

Electronic Failure Main Cause	Details
Contact Failure	Electron migration
	Thermal cycling
	Fire
	Environmental issue
	Mechanical issue
Electrical Overstress	Thermal
	Electron migrating
	Electric field related
	Electrostatic discharge

Table 12: Electronic component failure mechanisms

4.4 Development of General FTAs

There are many other potential failure modes, but in able to build an FTA, a top event has to be determined. Taking a gas processing and transportation scenario, one can decide to analyze the following three top events:

- Downtime (no gas flow)
- Choke State (less flow than required)
- Breakdown (repair required)

Breakdown does not necessarily imply downtime nor a choke state, since there might be redundancies in the system, however, repair costs have to be made. On the other hand, practically all downtime cases will also incur in breakdowns, while only some choke states will imply breakdown. These scenarios are to be analyzed separately in able to have a clearer, more detailed picture of these possibilities. They are to be considered independent in able to keep separate calculations, however, in reality there are strong interdependencies amongst them.

It is important to keep in mind that more than a set FTA, these will be guidelines, they should not be taken as is, but rather used as guidelines and adjusted. Since these are general, a certain degree of consistency is required across levels of the FTAs and thus some parts will include modes that otherwise would be omitted. Figure 10 will be used as the process to follow to build the trees.

4.4.1 Downtime

In able to find the most immediate general failure modes to this state, the question asked should be, how can the flow of gas in a particular system of the company completely stop?

The immediate most general reasons are the following:

- A major external leak (e.g. a major pipe completely breaks open)
- A major internal blocking (a main path is completely blocked)
- A total system shutdown (the processing/transport system stops)

One of these three have to happen in able to reach a downtime state. According to step three in Figure 10 a gate has to be chosen. In this case, any of the three happening would cause downtime, thus an "or" gate is selected. As step 4 of Figure 10 indicates, if any intermediary events are found at this level (events that can be further broken down), the immediate cause of them shall be found. Each one of these, major leak, major blocking and total system shutdown can be further broken down into additional modes and mechanisms. For example, a total system shutdown can happen due to:

- A planned shutdown (e.g. due to maintenance or inspection)
- An unplanned shutdown (
- An emergency shutdown (to avoid further potential loss)

Once again, any of these can be further broken down. Unplanned shutdowns can be then set up as the effect of:

- A power loss AND backup failure
- An electronic issue

Notice how power loss and backup failure require an "and gate". Either those two simultaneously or the electronic issue would cause an emergency shutdown. Electronic issue, is meant as the consequence of:

- Communication loss between equipment
- Critical data monitoring loss

This could further be explored, however, the FTA guides to be developed will have 5 levels, the top event (level 0) plus 4 others. Between zero and three clear set gates will be set. Meanwhile, the connections between level 3 and 4 will not be explicitly indicated, meaning they are specific for each system. At the same time, whenever using this on a real case, further levels in the FTA can be built.

Continuing with the Figure 10 methodology for every single branch, a full tree can be obtained. Appendix E shows the FTA guideline for the downtime state. Notice how between levels three and four there is a connection that includes both an "and gate" and an "or gate". The blocks in level four also seem to accumulate multiple activities. What this means is that depending on the specific system analyzed, at this level and in any deeper ones, the gates and blocks to be used are to be determined by the analyst; not all possible block modes are shown.

4.4.2 Choke State

The question to be asked for the choke state is, how can the flow of gas in a particular system of the company be lower than the requirement?

The immediate most general reasons are the following:

- External leak (not large enough to completely stop flow)
- Internal blocking (partial)
- A partial system shutdown (some, but not all flow is lost)
- Capacity limitations (equipment does not have the capacity to reach the required flow)

If any of these four happen, a choke state will be reached. Thus, an "or gate" is chosen. Following step 4 in Figure 10, the four level 1 blocks shall be further broken down. For the specific case of internal blocking:

- Electronic fault (valve shuts when it should not due to electronic issue)
- Non-Electronic (something physically blocks the interior of a pipe or equipment)

Level three under electronic fault can be:

- Thermal
- Interphase

These two simply require an “or gate” to be connected to the level above them since any of them would trigger such block. From level three to level four for the thermal block:

- Overheat
- Electrostatic discharge

Some additional level four blocks could be electron migration or fire. Continuing with the Figure 10 methodology for every single branch, a full tree is obtained and shown in Appendix F. Once again, from level four and further down, the analyst has to determine gates and blocks.

4.4.3 Breakdown

The question asked in this case is, how can an equipment come to a breakdown state and thus require repair costs? While several of the blocks for downtime and choke states are similar. This scenario changes significantly. It has to account for very different circumstances that can lead to the breakdown of different components and equipment.

The immediate most general reasons that were deemed to cause breakdown are:

- Buckling
- Thermal
- Fracture
- Wear
- Corrosion

If any of these happen breakdown could occur, thus an “or gate” is selected to link them to the top event. According to step three in Figure 10 a gate has to be chosen. Each of them is further broken down, in the case for corrosion the lower level becomes:

- Microbe
- Moisture
- Other Gas
- Material

Once again an “or gate” connects this level to its upper one. Continuing further down, the material block is extended into:

- Coating fault AND increasing temperature

In this case, an "and gate" is in order. This is because, for a material related corrosion failure (original material used in equipment or component) to occur, the coating used in it has to be faulty and high temperature present. Finally, level four includes things like

- Insulation material wear
- Cooling problems

Another potential block for this branch at level four is faulty coating material used. Continuing with the Figure 10 methodology for all branches, Appendix G is obtained. This tree contains more branches than the past two and uses "and gates" more often.

4.5 FTAs into Financial Losses

The general FTAs were developed to serve as a guideline in able to obtain the following critical technical parameters:

- **ΔPc'**: (difference between production loss costs of unreliability without replacement and with replacement)
- **ΔEc'**: (difference between spare part costs of unreliability without replacement and with replacement)
- **ΔLc'**: (difference between repair labor costs of unreliability without replacement and with replacement)

Both the Downtime and Choke states result in processing or transport losses, which can ultimately be linked to Pc for either a replacement or non-replacement case. Therefore, in able to calculate ΔPc', one requires to know what fraction of the time the system to be analyzed finds itself in either a Downtime or a Choke state for both Pc_R and Pc_N. This can be done by using availability numbers for all blocks in these two FTAs. An availability number will then be obtained for the top events. This can then be transformed into financial losses by multiplying the fraction obtained at the top events by the average production loss value for each case. To obtain ΔPc', subtract the replacement scenario value obtained from the non-replacement one.

On the other hand, the Breakdown FTA can be linked to Ec and Lc for either a replacement or a non-replacement case. This is because every time the Breakdown state is reached a component needs to be repaired, this entails both spares and repair labor costs. However, unlike the other two FTAs, availability here would not help to obtain these technical parameters. Instead, failure rate shall be used. Once the top event's failure rate is calculated using the lower levels, this can be translated into "breakdowns/year" and then multiplied by the average cost per breakdown. This will yield Ec + Lc for a specific case. Two calculations are required, one without replacement and one with replacement. The difference between those two will be ΔEc' + ΔLc'.

Usually the FTAs used before replacement will also be valid after such. However, if the system where the replacement is made suffers changes that alter interdependencies or redundancy, a different FTA would have to be used for each case. Calculating the critical technical parameter is the real limiting factor in this project. It is the largest challenge. The following chapter will explore a mock case in able to better illustrate how the model suggested can be used.

5 Mock Case Presentation

In able to illustrate what the developed model is capable of doing and how to use it, a mock case will be studied. This is an imaginary case, and while it tries to keep as many variables as possible close to a real scenario, it is important to keep in mind that it is nothing but a way of showcasing the model. The results obtained in this section will dictate what requires to be changed when it is tested against a real case.

5.1 Mock Scenario

Inspired on a recent motor starter replacement case that Gassco AS was involved with, this Mock case will base itself on a similar scenario.

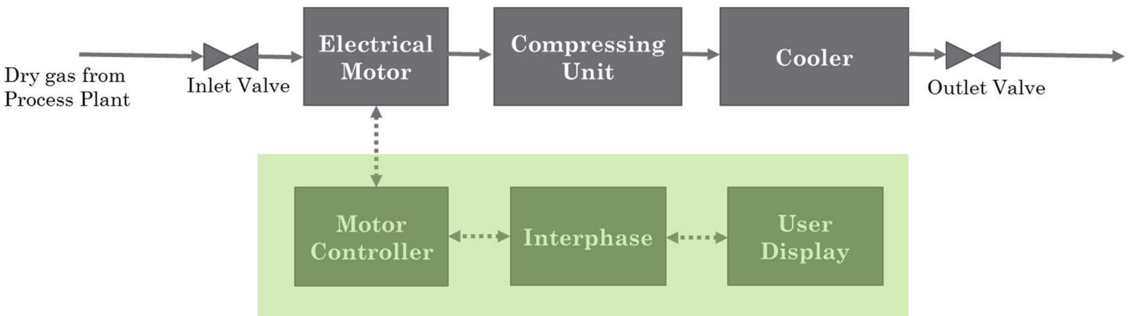


Figure 26: Mock scenario overview

Concept	Value	Units
Production	**15**	Mill scm/day
Selling Price	**2**	NOK/scm
Equip time to obsolescence	**10**	Years
Replacement Investment	**200**	Mill NOK
Cost of Capital	**5**	%
Loan Yearly Interest Rate	**2.8**	%
Tax Rate	**40**	%
Overly Costs (no rep)	**16**	Mill NOK/year
Reactive Costs (no rep)	**2**	Mill NOK/year
Overly Costs (replacement)	18	Mill NOK/year
Reactive Costs (replacement)	**0.5**	Mill NOK/year

Table 13: Mock case key information

The system considered for this mock case is a compressing unit. This unit has an export compressor that is powered by an electrical motor. Such motor is in turn powered by a motor controller (motor driver). This motor controller is electronically linked to a user display through an interphase. The mock case will analyze the possibility of replacing the motor controller-interphase-user display assembly with a new version.

All the values shown in Table 13 are to be considered constant for the entirety of the analysis period. The production value is close to what a single export compressor handled by Gassco AS transports. The gas selling price and the loan interest rate are based on a Gassco AS's internal economic planning document. The Cost of Capital is similar to the rate of return expected from shareholders in companies similar to Gassco AS. The rest of the values in Table 13 are simply assumed.

5.2 Model Application

(27) Will be used as a valid equation for the initial solution of this mock case. It means that the following equation is valid (keeping in mind all Assumptions for (27)).

$$[(\Delta Pc' + \Delta Ec' + \Delta Lc' + \Delta Fc' + \Delta Oc' + \Delta Rc')] > \frac{\left[\frac{IC_R}{n}\right] * \left[1 + CoC * \left(\frac{n-1}{2}\right) - TR\right]}{(1 - TR)}$$

The following variables from (27) are directly known:

- ICR: 200 mill NOK
- CoC: 5%
- TR: 40%
- n: 10

These are all on the right hand side of the inequality and thus that side can be calculated. After performing the calculations:

$$\frac{\left[\frac{IC_R}{n}\right] * \left[1 + CoC * \left(\frac{n-1}{2}\right) - TR\right]}{(1 - TR)} = 27.5\ Mill\ NOK$$

The following variables can be obtained indirectly: ΔFc', ΔOc' and ΔRc'.

According to the information above:

- Oc_N: 16 mill NOK
- Rc_N: 2 mill NOK
- Oc_R: 18 mill NOK
- Rc_R: 0.5 mill NOK

Thus:

ΔOc' = 16 – 18 = **-2 mill NOK**

ΔRc' = 2– 0.5 = **1.5 mill NOK**

ΔFc' can be calculated with the interests that will have to be paid due to the loan required for the initial investment. Fc_N is equal to zero since no investment is made without replacement. In this case, no loans are required nor owed.

Thus

ΔFc' = 0 – Fc_R = **-Fc_R**

Fc_R in turn is the yearly spending in interest payments. Since all deltas are assumed to be equal, Fc_R has to be such that interest is paid for the whole period is evenly distributed through all years. If interest is paid yearly, the amortized equal payments are calculated with:

$$A = P * \frac{r * (r+1)^n}{(1+r)^n - 1} \tag{29}$$

Where:

- A: Payment Amount per Period
- P: Initial Principal (200 million)
- r: Interest Rate per Period (2.8 per year)
- n: Total Number of Payments/Periods (10 years)

A in this case would be equal to 23.21. Of this 20 million are capital payments and 3.21 interest payments. Therefore:

ΔFc' = **-3.21 mill NOK**

5.2.1 Downtime

The three variables left for calculation are ΔPc', ΔLc' and ΔEc'. The downtime and choke state summed together will give Pc; two different calculations are required, before and after replacement. For Downtime, the right-most branch of the guideline FTA is considered to be the key. The major leak and internal blockage branches do not apply here, since the system is composed of electronics. From Appendix E, the following part is taken:

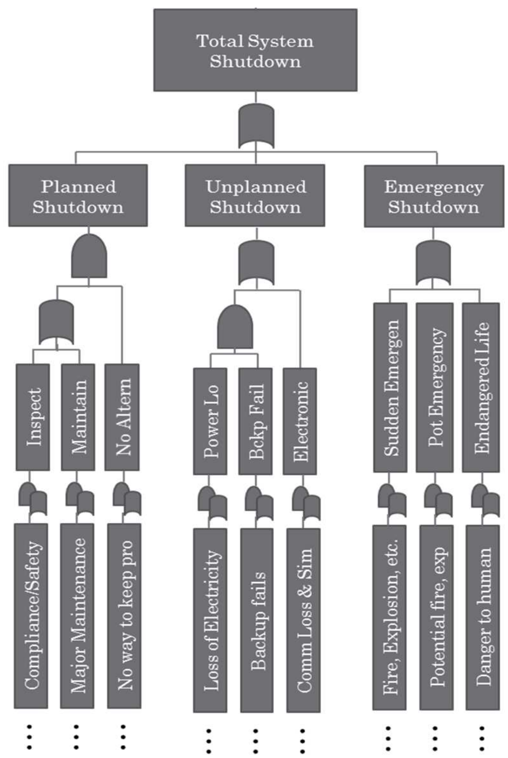


Figure 27: Appendix E guideline focus branch

Further adjustment for this specific case yields:

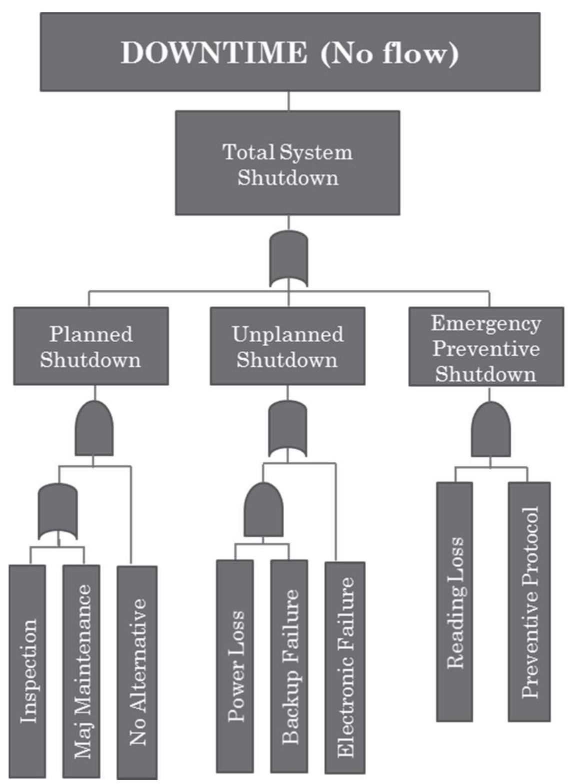


Figure 28: Downtime FTA mock case

Note that only 3 levels below the top event were deemed necessary. This is perfectly fine if no further details are required to reach a result for the top event. The replacement will not alter any interdependencies nor redundancy, and therefore Figure 28 is valid both with and without replacement. MTTR and MTTF data is assumed to be available and thus availability calculated for every block beneath the top event with (4). Figure 28 will then be populated for both cases on the lower level. Following the calculation methodology presented in 2.3.4 the upper levels can be calculated until the top event is reached for both non-replacement and replacement. All blocks are considered to be mutually exclusive for simplicity. Availability data has no specific origin, and is all assumed.

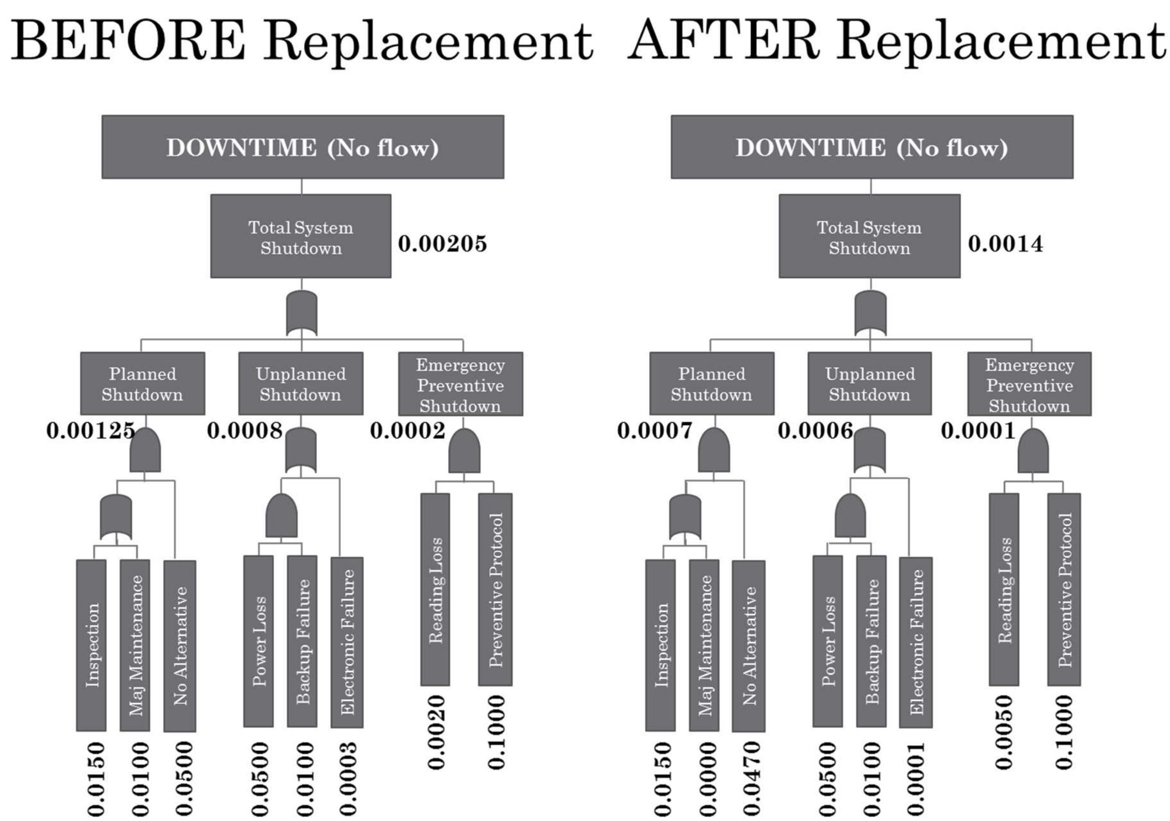


Figure 29: Mock case downtime comparison

Based on the results obtained and shown in Figure 29, the non-replacement case is in a downtime state 0.205% of the time, while the replacement one is in it 0.14% of the time.

Using the fact that production requirements are a continuous 20 million scm/day and that every scm is sold at 2 NOK, one can calculate how much Pc is lost on the downtime states for both circumstances. The calculation has to be done for one period (one year).

$$\boldsymbol{PC_N}(downtime) = 0.00205 * \frac{15\ mill\ scm}{day} * \frac{2\ NOK}{scm} * \frac{365\ days}{1\ year} = \frac{\mathbf{22.45\ mill\ NOK}}{\mathbf{year}}$$

Meanwhile:

$$PC_R(downtime) = 0.0014 * \frac{15\ mill\ scm}{day} * \frac{2\ NOK}{scm} * \frac{365\ days}{1\ year} = \frac{\mathbf{15.33\ mill\ NOK}}{\mathbf{year}}$$

Therefore:

$$\boxed{\Delta Pc'(downtime) = \frac{\mathbf{7.12\ mill\ NOK}}{\mathbf{year}}}$$

5.2.2 Choke State

This state will calculate the complimentary part of ΔPc'. Focus will be placed on the two right-most branches of the FTA guideline for Choke State found in Appendix F. This is once again because it is electronic components that can fail, thus leaks and blockages do not apply.

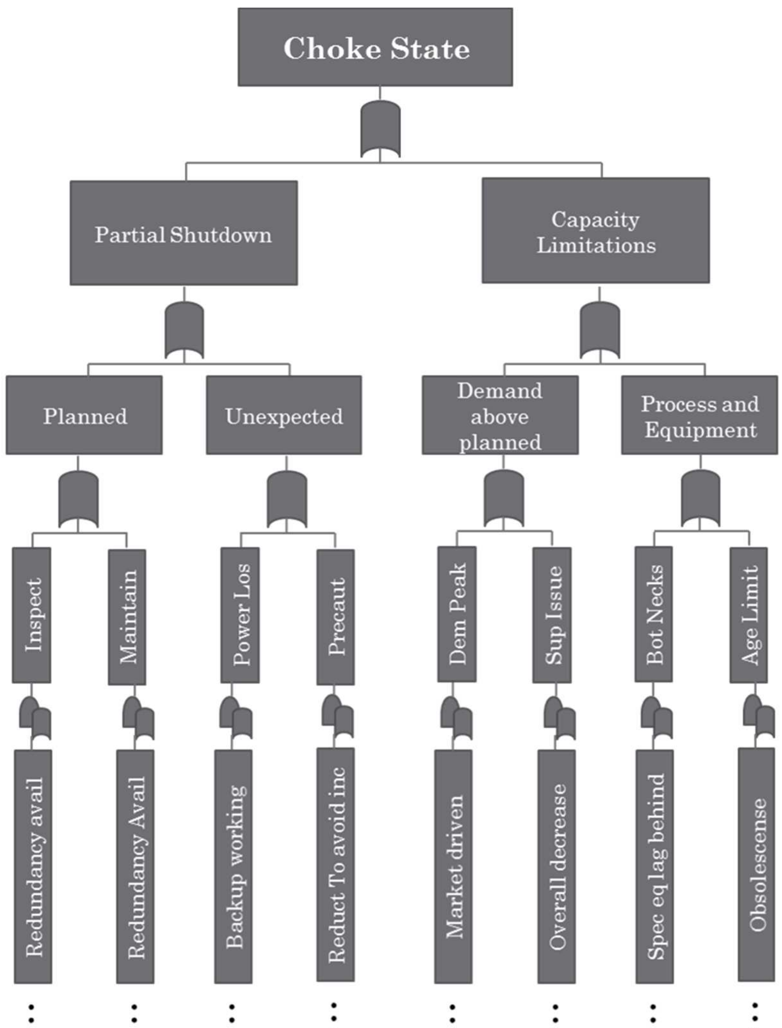


Figure 30: Appendix F guideline focus branches

Adjusting to tailor for this specific case:

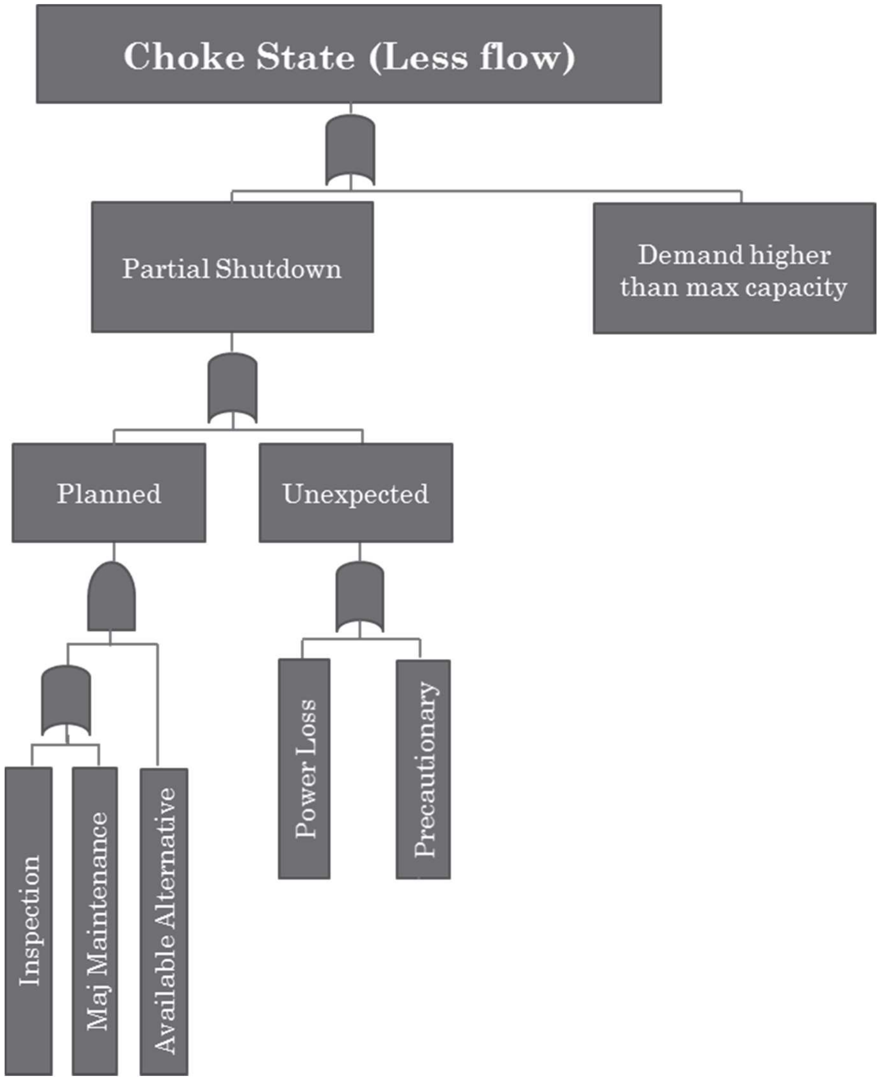


Figure 31: Choke state FTA mock case

Note that for the left branch 3 levels below the top event were deemed necessary while on the right branch only one level sufficed. To calculate the top event one assumes that data for the lowest levels of each branch are available and the upper levels can be calculated with (4). The replacement will not alter any interdependencies nor redundancy, which makes Figure 31 valid for both replacement and non-replacement. All blocks are considered to be mutually exclusive for simplicity. Availability data has no specific origin, and is all assumed.

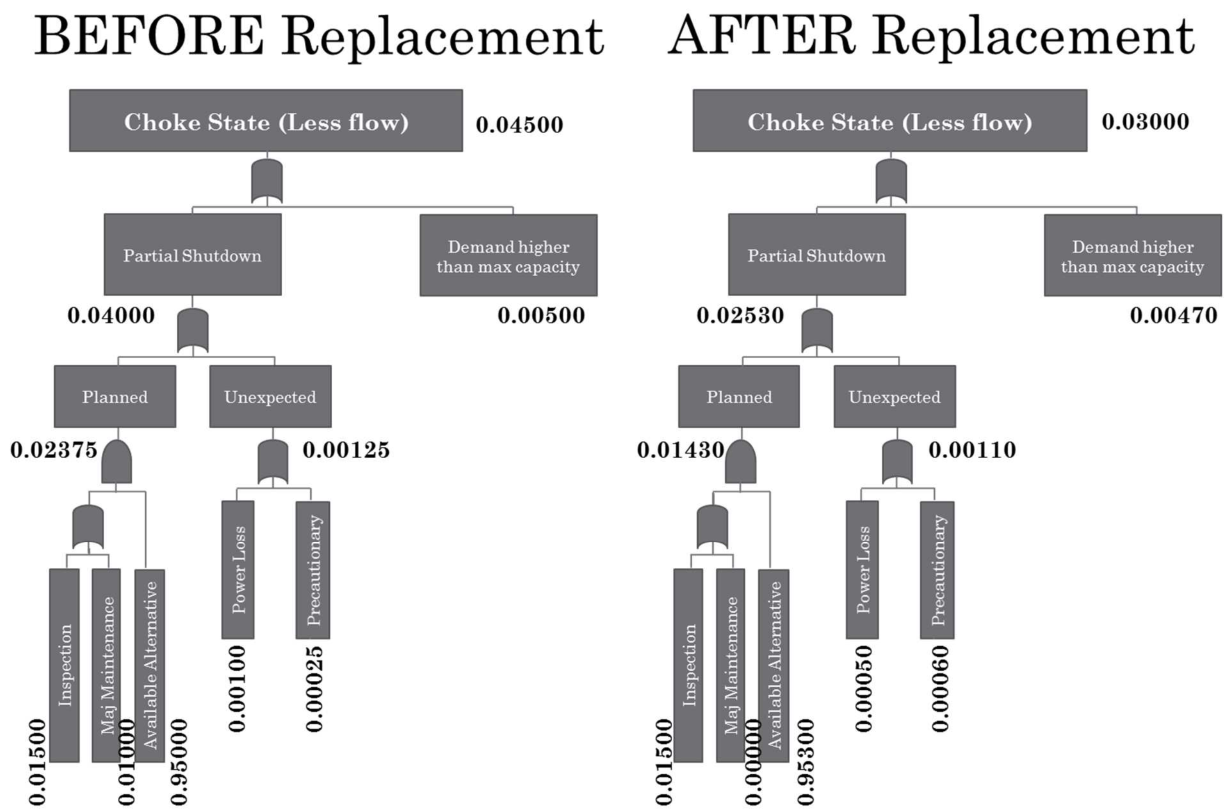


Figure 32: Mock case choke state comparison

Based on the results obtained and shown in Figure 32, the non-replacement case is in a choke state 4.5% of the time, while the replacement one is in it 3% of the time. Whenever in a choke state, the production rate is in average 1.5 million scm/day less than the required (assumption). Since every scm is sold at 2 NOK, one can then calculate how much Pc is lost on the choke states for both circumstances.

$$\boldsymbol{PC_N}(choke\ state) = 0.045 * \frac{1.5\ mill\ scm}{day} * \frac{2\ NOK}{scm} * \frac{365\ days}{1\ year} = \frac{\mathbf{49.28\ mill\ NOK}}{\mathbf{year}}$$

Meanwhile:

$$\boldsymbol{PC_R}(choke\ state) = 0.030 * \frac{1.5\ mill\ scm}{day} * \frac{2\ NOK}{scm} * \frac{365\ days}{1\ year} = \frac{\mathbf{32.85\ mill\ NOK}}{\mathbf{year}}$$

Therefore:

$$\boxed{\boldsymbol{\Delta Pc'}(choke\ state) = \frac{\mathbf{16.43\ mill\ NOK}}{\mathbf{year}}}$$

The total ΔPc' is the sum of the downtime and choke states, thus:

$$\Delta Pc' = \frac{7.12\ mill\ NOK}{year} + \frac{16.43\ mill\ NOK}{year} = \frac{23.55\ mill\ NOK}{year}$$

5.2.3 Breakdown

This state will calculate both ΔEc and ΔLc. Focus will be placed on the second and third sub-branches of the second branch (left to right) and the second sub-branch of the fifth branch. Once again, this is because the case analyzes electronic components that can fail, thus the other sub-branches are deemed unnecessary.

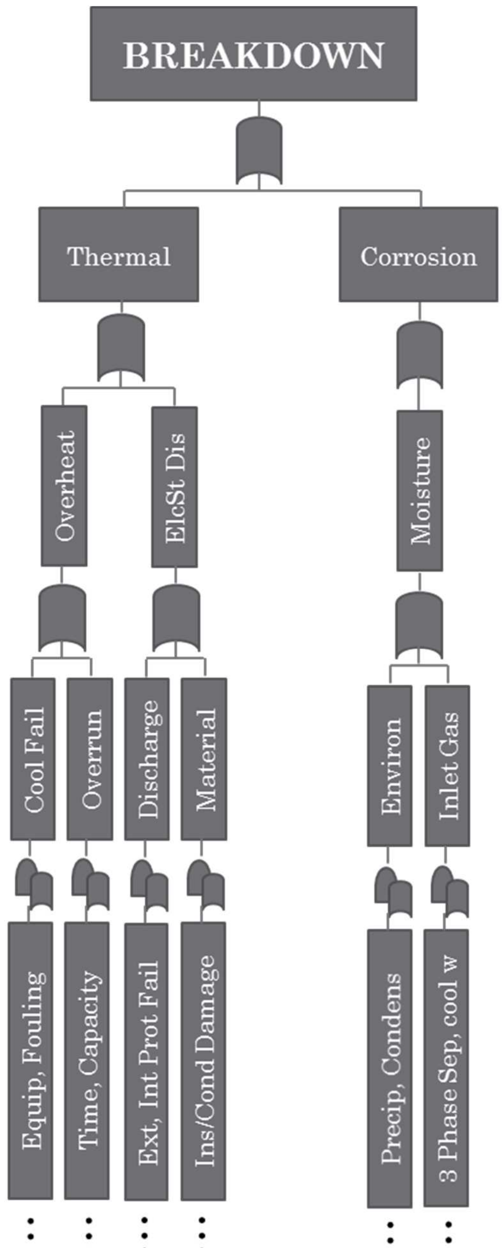


Figure 33: Appendix G guideline focus branches

Adjusting the figure above to a specific one for this case:

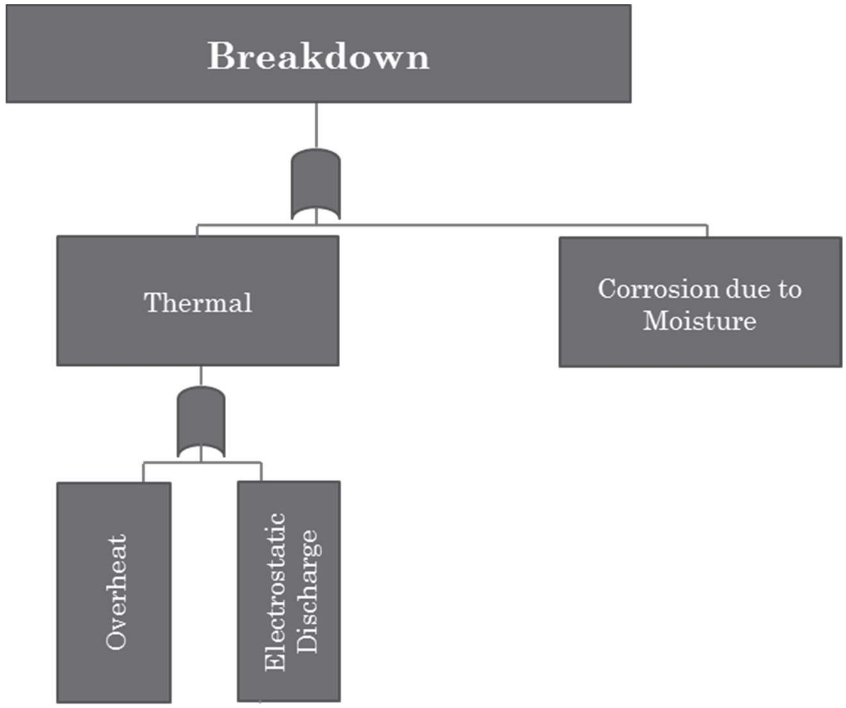


Figure 34: Breakdown FTA mock case

Here, the left branch barely has two levels below the top event and the right branch has only one. This is because no further details were thought to be necessary. To calculate the top event, an assumption is made that the lower levels are known. Afterwards, (4) is used to calculate all levels above. The replacement will not alter any interdependencies nor redundancy, which makes Figure 34 valid for both replacement and non-replacement. All blocks are considered to be mutually exclusive for simplicity. For the breakdown case, availability numbers are not used in the blocks. One rather uses failure rates (frequencies). The frequencies that follow are all assumptions and have no specific origin.

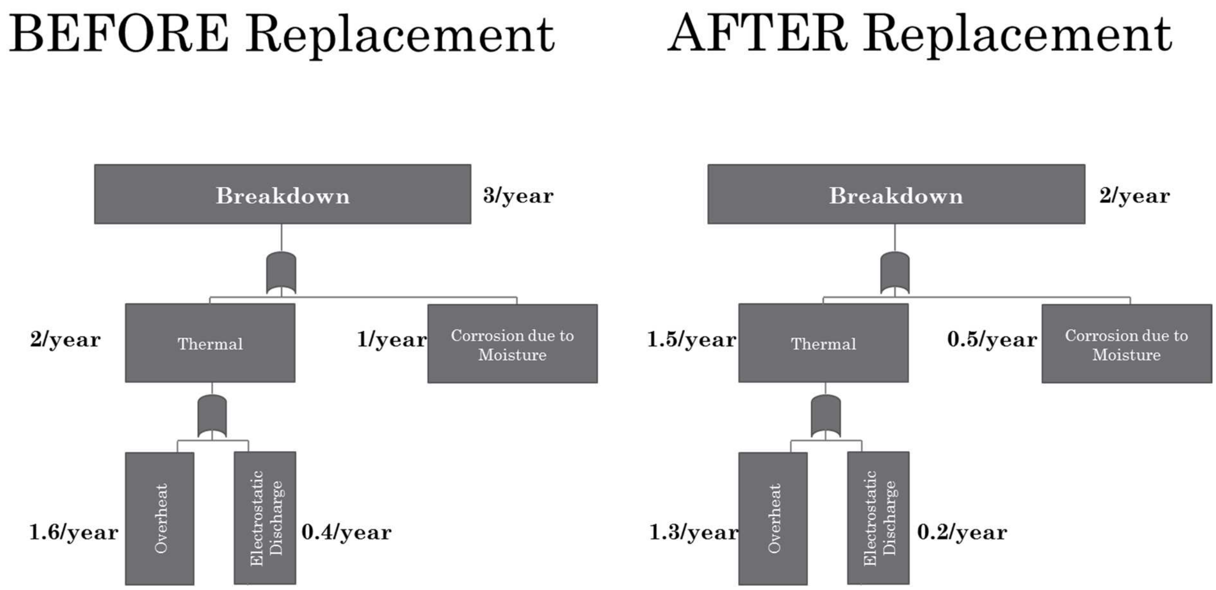


Figure 35: Mock case breakdown comparison

Before replacement, there are 3 expected breakdowns per year, while after replacement only 2 per year are predicted. The average repair cost per breakdown is divided in spare costs (Ec) and labor repair costs (Lc). They are assumed to be equal to the figures shown in Table 14 below.

Concept	Value	Units
Spare Part Cost (no rep)	**2.0**	Mill NOK
Labor Repair Cost (no rep)	**2.0**	Mill NOK
Spare Part Cost (replacement)	**3.0**	Mill NOK
Labor Repair Cost (replacement)	**2.5**	Mill NOK

Table 14: Spare part and labor repair costs for mock case

In combination with the breakdowns per year previously obtained, the spare part costs of unreliability for non-replacement are:

$$\boldsymbol{Ec_N} = \frac{3\ breakdown}{year} * \frac{2\ mill\ NOK}{breakdown} = \frac{\boldsymbol{6\ mill\ NOK}}{\boldsymbol{year}}$$

In case replacement takes place:

$$\boldsymbol{Ec_R} = \frac{2\ breakdown}{year} * \frac{3\ mill\ NOK}{breakdown} = \frac{\boldsymbol{6\ mill\ NOK}}{\boldsymbol{year}}$$

Thus, the difference is:

$$\boxed{\boldsymbol{\Delta Ec'} = \frac{6\ mill\ NOK}{year} - \frac{6\ mill\ NOK}{year} = \frac{\mathbf{0\ mill\ NOK}}{\mathbf{year}}}$$

Similarly for labor repair costs without replacement:

$$\boldsymbol{Lc_N} = \frac{3\ breakdown}{year} * \frac{2\ mill\ NOK}{breakdown} = \frac{\mathbf{6\ mill\ NOK}}{\mathbf{year}}$$

For the replacement case:

$$\boldsymbol{Lc_R} = \frac{2\ breakdown}{year} * \frac{2.5\ mill\ NOK}{breakdown} = \frac{\mathbf{5\ mill\ NOK}}{\mathbf{year}}$$

Thus, the difference is:

$$\boxed{\boldsymbol{\Delta Lc'} = \frac{6\ mill\ NOK}{year} - \frac{5\ mill\ NOK}{year} = \frac{\mathbf{1\ mill\ NOK}}{\mathbf{year}}}$$

All that is left to do is assemble all the variables previously obtained.

5.2.4 Constant Deltas Results

All variables are now known. The inequality has to be checked to determine if the investment should be made. The left hand side becomes:

$\Delta Pc' + \Delta Ec' + \Delta Lc' + \Delta Fc' + \Delta Oc' + \Delta Rc'$ = 23.55 + 0 +1 + (-3.21) + (-2) + 1.5 = **20.84 mill NOK**

Both sides of the equation now have to be compared.

$$[(\Delta Pc' + \Delta Ec' + \Delta Lc' + \Delta Fc' + \Delta Oc' + \Delta Rc')] > \frac{\left[\frac{IC_R}{n}\right] * \left[1 + CoC * \left(\frac{n-1}{2}\right) - TR\right]}{(1 - TR)}$$

$$\boxed{\mathbf{20.84} > \mathbf{27.5}}$$

The left hand side of the equation is lower than the right side, different from what the inequality mandates. This means that there is no financial justification to replace the system analyzed. There might be a chance, however, that some of the parameters used to calculate the inequality might actually be different.

5.2.5 Minimum/Maximum Required Parameter Values

What then, if the ΔXc's originally used were actually different? Justifying the replacement could be likelier in this scenario. For this analysis, (28) will be recurred to, this is to have the same benchmark as in the following section (Changing Deltas Analysis).

$$\sum_{i=1}^{n}[\Delta Pc' + \Delta Ec' + \Delta Lc' + \Delta Fc' + \Delta Oc' + \ \Delta Rc'] > \frac{[IC_R] * \left[1 + CoC * \left(\frac{n-1}{2}\right) - TR\right]}{(1-TR)}$$

Without any difference in ΔXc's, (28) is essentially the same as (27). This is because all deltas are constant and thus their sum simply becomes "n*ΔXc'".

$$n * [\Delta Pc' + \Delta Ec' + \Delta Lc' + \Delta Fc' + \Delta Oc' + \ \Delta Rc'] > \frac{[IC_R] * \left[1 + CoC * \left(\frac{n-1}{2}\right) - TR\right]}{(1-TR)}$$

One could then divide both sides by "n" and obtain (27). However, in able to keep the exact same expression on the right hand side regardless of the changes on the left, this will be avoided in this analysis. To have a starting point, the value of (28) is calculated in case deltas remain constant throughout the 10 year period of this mock case (all values previously used remain valid).

$$10 * [23.55 + 0 + 1 - 3.21 - 2 + \ 1.5] > \frac{[200] * \left[1 + 0.05 * \left(\frac{10-1}{2}\right) - 0.4\right]}{(1-0.4)}$$

The Inequality then becomes:

$$\boxed{\mathbf{208.4 > 275.0}}$$

Notice that this is exactly the same value obtained in 5.2.4, simply multiplied by "n". This is because in this case, this is not on a "yearly basis" but rather considers the full length of the period and the sum of the losses incurred throughout it. The result above still, as expected, shows no justification for replacement. Nonetheless, there is a possibility that by changing certain parameters, the left hand side will be able to fulfill the inequality by becoming greater than the right side. Each ΔXc' is dependent on at least one parameter. It is also possible that rather than the left side growing to match the right side, it is the latter that is reduced to a low enough level to satisfy the inequality. This then leads to the question, what is the minimum (or maximum) value these parameters must have in able to satisfy the inequality and thus justify a replacement decision?

With the help of a spreadsheet software, a document was created in able to help analyze scenarios for the proposed model. This document is named "Replacement Analysis Tool" and will be referred to as "RAT" from here on. Table 15 below shows an overview of the parameters that will be considered as potential change sources to satisfy (28).

Inequality Side	General Parameter	Specific Linked Parameter
Left	ΔPc’	Downtime State
		Choke State
Left	ΔEc’	Number of Breakdowns
		Spare Part Avg. Cost
Left	ΔLc’	Number of Breakdowns
		Labor Repair Avg. Cost
Left	ΔFc’	Loan Interest Rate
Left	ΔOc’	Non-Specific
Left	ΔRc’	Non-Specific
Right	n	Lifetime
Right	IC	Non-Specific
Right	CoC	Non-Specific
Right	TR	Non-Specific

Table 15: RAT changing parameter overview

The parameters shown in Table 15 apply for both “replacement” and “non-replacement” cases. The following case to explore still considers constant yearly losses, but tries to find the value of each specific parameter that fulfills (28). With the help of the RAT, the minimum or maximum values for each parameter in able to justify a replacement are sought. It is important to consider that depending on the case, for some general parameters no positive value in their linked specific parameters might be enough (by itself) to satisfy (28). These cases will be marked as NA (Non-attainable).

Considering every other variable to remain exactly the same, these are the RAT findings:

Changing Parameter	Case	Original Value	Required Value
Downtime State	Non-Replacement	0.205%	Minimum 0.266%
	Replacement	0.140%	Maximum 0.079%
Choke State	Non-Replacement	4.5%	Minimum 5.11%
	Replacement	3.0%	Maximum 2.39%
Number of Breakdowns	Non-Replacement	3 per year	Min. 4.67 per year
	Replacement	2 per year	Max. 0.79 per year
Spare Part Avg. Cost	Non-Replacement	2 Mill NOK/Fail	Min 4.22 Mill NOK/F
	Replacement	3 Mill NOK/Fail	NA
Labor Repair Avg. Cost	Non-Replacement	2 Mill NOK/Fail	Min 4.22 Mill NOK/F
	Replacement	2.5 Mill NOK/Fail	NA
Loan Interest Rate	Replacement	2.8% per year	NA
Overly Costs	Non-Replacement	16 Mill NOK/year	Min. 22.6 Mill NOK/y
	Replacement	18 Mill NOK/year	Max 11.3 Mill NOK/y
Reactive Costs	Non-Replacement	2 Mill NOK/year	Min. 8.7 Mill NOK/y
	Replacement	0.5 Mill NOK/year	NA
n (Lifetime)	General	10 years	Min. 16 years
IC	General	200 Mill NOK	Max. 156.6 Mill NOK
CoC	General	5%	Max. 0.6%
TR	General	40%	NA

Table 16: Mock case minimum/maximum required parameter values (constant deltas)

Table 16 proves that the inequality (28) can be accomplished by changing one of many variables. Nevertheless, the difference in some of these would have to be extreme. It is likelier that (28) be satisfied by a combination shifts in several parameters. In any case, this only considers constant ΔXc's. Another way in which the replacement could be deemed convenient without altering the initial conditions is to have the ΔXc's change through time. This shall be further examined.

5.2.6 Changing Deltas Analysis

Not only is this a supplementary possibility for fulfilling (28), but it is also important to consider that this is a more likely setting. This is because parameters like downtime and choke time states as well as the breakdowns and spare/labor repair costs are probably going to increase with time. While this will likely be true for both "replacement" and "non-replacement", the rate of growth of the latter will be steeper than for the former.

The RAT also has the capacity to compute the sum of different changing ΔXc's. It does so by considering constant cumulative yearly growth percentages for the changing parameters.

Changing Parameter	Case	Original Value	Required Growth
Downtime State	Non-Replacement	0.205%	4.7% yearly
	Replacement	0.140%	NA
Choke State	Non-Replacement	4.5%	Minimum 2.3% yearly
	Replacement	3.0%	NA
Number of Breakdowns	Non-Replacement	3 per year	Min. 13.4% yearly
	Replacement	2 per year	NA
Spare Part Avg. Cost	Non-Replacement	2 Mill NOK/Fail	Min. 13.4% yearly
	Replacement	3 Mill NOK/Fail	NA
Labor Repair Avg. Cost	Non-Replacement	2 Mill NOK/Fail	Min. 13.4% yearly
	Replacement	2.5 Mill NOK/Fail	NA
Loan Interest Rate	Replacement	2.8% per year	NA
Overly Costs	Non-Replacement	16 Mill NOK/year	Min. 6.5% yearly
	Replacement	18 Mill NOK/year	NA
Reactive Costs	Non-Replacement	2 Mill NOK/year	Min 25.75% yearly
	Replacement	0.5 Mill NOK/year	NA

Table 17: Mock case changing delta required growth

The tool does not consider it possible for a variable to have negative growth through time, thus, changes for "replacement" cases don't result in the satisfaction of (28). Similar to Table 16, extreme cases are also presented on Table 17 since only one variable is considered to change through time. Once again, the more likely scenario to fulfill the inequality would be a combination of some, if not all of them. Please refer to Appendix I for RAT generated charts in which the sensitivity of several variables to their growth rate through time is presented.

Using the RAT, several scenarios were analyzed to try to find a plausible one that could deem the replacement investment sound. This was done without altering any of the initial values of any parameter. Eventually, it was noticed that the inequality could be fulfilled by taking the following two steps:

1. Set every non-replacement variable to a 2% yearly growth
2. Set every “replacement” variable to a 1% yearly growth

Year	PcN	PcR	EcN	EcR	LcN	LcR	FcN	FcR	OcN	OcR	RcN	RcR	ΣXN	ΣXR	Gap (ΣXN-ΣXR)
1	71.72	48.18	6.00	6.00	6.00	5.00	0	3.21	16.00	18.00	2.00	0.50	101.72	80.89	20.84
2	73.16	48.66	6.24	6.12	6.24	5.10	0	3.21	16.32	18.18	2.04	0.51	104.00	81.78	22.23
3	74.62	49.15	6.49	6.24	6.49	5.20	0	3.21	16.65	18.36	2.08	0.51	106.34	82.67	23.66
4	76.11	49.64	6.76	6.37	6.76	5.31	0	3.21	16.98	18.55	2.12	0.52	108.73	83.58	25.14
5	77.63	50.14	7.03	6.50	7.03	5.41	0	3.21	17.32	18.73	2.16	0.52	111.18	84.51	26.67
6	79.19	50.64	7.31	6.63	7.31	5.52	0	3.21	17.67	18.92	2.21	0.53	113.69	85.44	28.25
7	80.77	51.14	7.61	6.76	7.61	5.63	0	3.21	18.02	19.11	2.25	0.53	116.26	86.38	29.88
8	82.39	51.66	7.92	6.90	7.92	5.75	0	3.21	18.38	19.30	2.30	0.54	118.90	87.34	31.56
9	84.03	52.17	8.24	7.04	8.24	5.86	0	3.21	18.75	19.49	2.34	0.54	121.60	88.31	33.29
10	85.72	52.69	8.57	7.18	8.57	5.98	0	3.21	19.12	19.69	2.39	0.55	124.37	89.29	35.07
															276.58

Table 18: Mock case changing deltas for inequality fulfillment summary

Table 18 shows the values of the main components of the left side of the inequality. The last column shows the yearly gap between the non-replacement and the replacement cases. On its bottom, the sum of all yearly gaps is found; this is equal to the left side of the inequality according to (28). Since the right side did not suffer any changes, the inequality then becomes:

$$\mathbf{276.58 > 275.0}$$

This scenario now calls for a replacement. If one looks closer into Table 18, in the last column, one can notice that the yearly gap went from just under 21 million NOK to around 35 million NOK in ten years. In this case, the variable that mostly affected this was PcN. With a yearly 2% increase, it went from around 72 to almost 86 million NOK. The rest of the variables had a much lesser impact since their initial value was much lower.

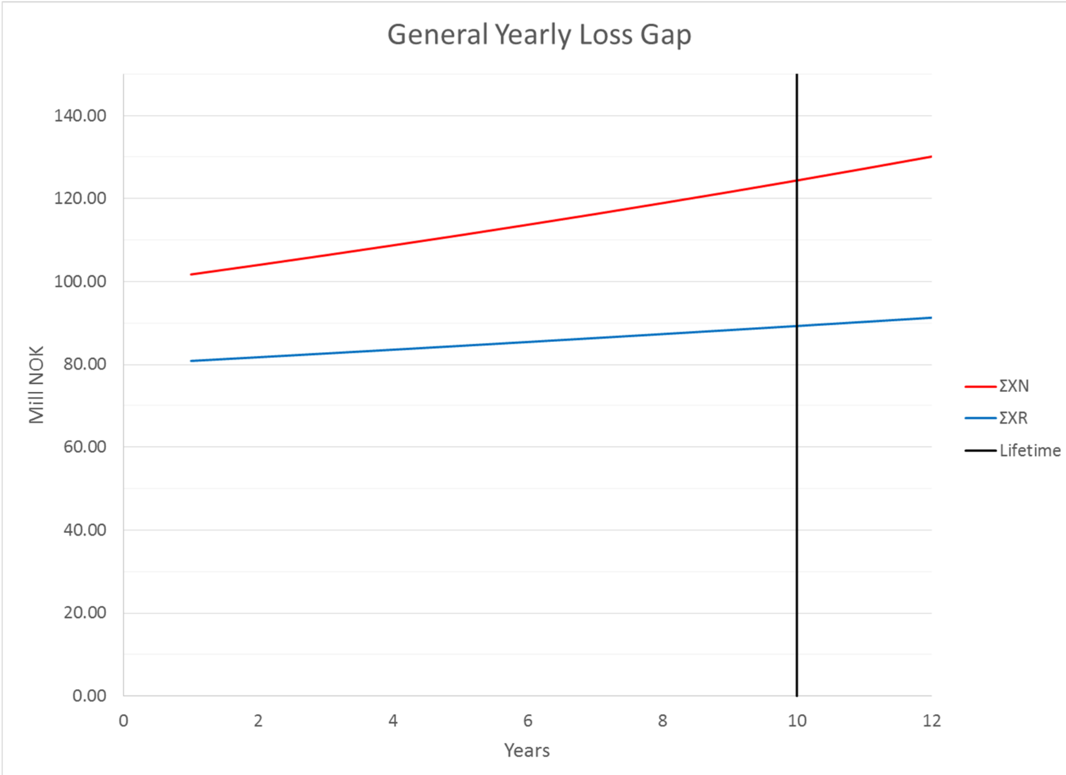


Figure 36: Mock case yearly gap with changing deltas

Figure 36 shows the evolution of the yearly gap for the mock case when replacement variables grow 1% yearly and non-replacement ones do so at a 2% rate. This seems to be sensible considering that in a non-replacement scheme, obsolete equipment would have to be dealt with.

5.3 Model Evaluation

The mock case was performed with success. The model seems to be solid enough to come with a direct "yes or no answer" towards the replacement dilemma. The development of the RAT is a quintessential part of using the model since it allows for a much faster analysis of different scenarios. Since this was a mock case, some of the initially used numbers were modified in able to make the sides of the inequality be closer to one another. It was desired that the left side be lower in the constant deltas case in able to better showcase how that does not necessarily guarantee that a replacement is not justifiable.

Overall, this phase can be deemed a success. However, there are several things that remain to be tested with a real case. The first that comes to mind is obtaining data. This mock case assumed most of its figures and thus did not have any issues achieving the final result. It is unlikely that things will go as smoothly with real information. The FTA guidelines are also yet to be proven with a real case. It seems, however, like there are cases where simply elaborating RBDs or FTAs from complete scratch might be more convenient.

6 Real Case Presentation

After having looked promising with a mock example, the proposed model will be faced with a real case. The objective is to test if the model can hold up in situations where circumstances might not be ideal. After this test, suggestions shall be made to adjust it to make the most out of its potential. The case to be analyzed was selected by Gassco AS in collaboration with one of its partners.

6.1 Scenario

The potential replacement of two UPS (uninterrupted power supply) units is to be analyzed. These units are responsible for feeding two compressors at different substations. They regulate peaks and valleys in electric supply. They also have batteries that can act as a backup feed in case the electrical grid has a problem.

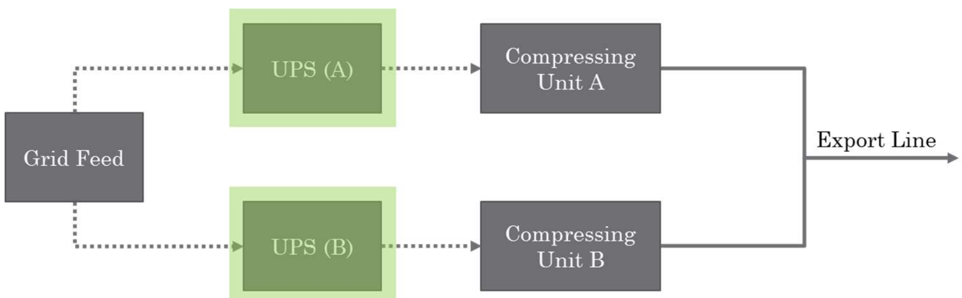


*Figure 37: UPS case system layout ***

**Disclaimer: Figure 37 shows each compressing unit connected to the electrical grid, through a UPS unit. This is an important simplification, since it is not the compressor itself that is connected to the UPS, but rather some of its critical support systems. Therefore, Figure 37 works under the assumption that if any of these support systems fails to be fed, the compressing unit will not be able to perform its task.

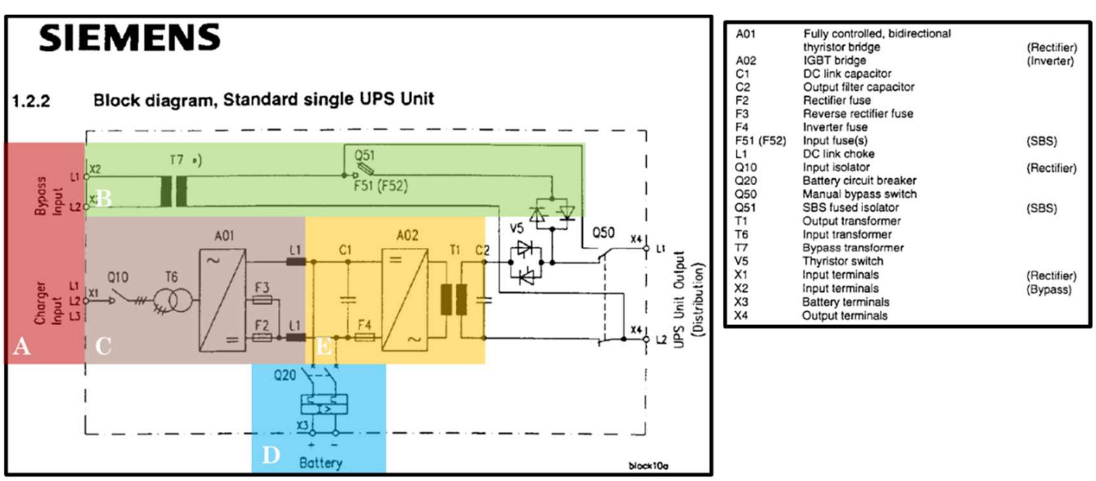


Figure 38: Single UPS Schematic

Other than the previously mentioned battery feature, the UPS units also have other internal redundancies. A good overview of these was available on provider operation manuals. The UPS unit system can be divided into 5 main groups as shown in Figure 38. They each have respective sub-components, however, for the objective of this project, a general understanding of these five groups will suffice. Table 19 below gives an overview of these groups and their functions.

Group Name	Group Letter	Function
Electrical Grid	A	Main electrical feed source
Bypass Switch	B	Bypass rectifier and inverter if necessary
Rectifier	C	Regulate grid feed and charge battery
Battery	D	Backup electrical feed source
Inverter	E	Change DC to AC

Table 19: UPS component overview:

If everything is operating under normal conditions, the electricity will flow from the grid through both the rectifier and inverter (Path A-C-E)

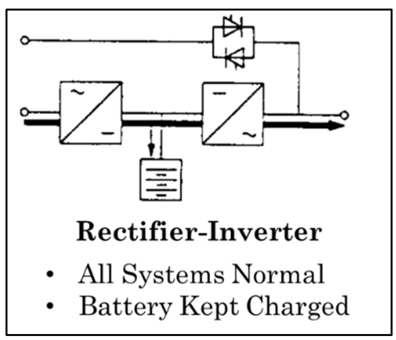


Figure 39: Normal system path

If there is a problem with the main feed or with the rectifier, the electricity will flow from the battery directly into the inverter (Path D-E)

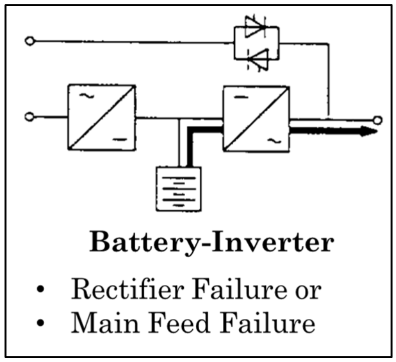


Figure 40: Battery system path

Finally, if there is an overload or a problem with the inverter, the electricity will flow from the grid feed and through the bypass (Path A-B)

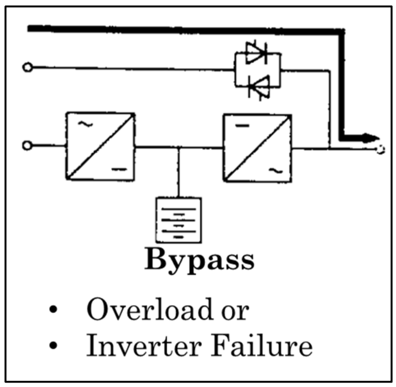


Figure 41: Bypass system path

According to the circumstances previously presented, the objective of this chapter is to analyze if replacing the UPS units with new ones makes financial sense. This will be done by using the proposed methodology and a similar approach as the one presented in the mock case will be used.

6.2 Model Application

The first step is to determine downtime, choke and breakdown states. The FTA guidelines will be used to develop specific FTA's to accomplish this. Nevertheless, for the current scenario, the choke state FTA will not be needed since electrical feed is either available or not (it cannot be partial). Using Appendix E the following FTA is developed for Downtime.

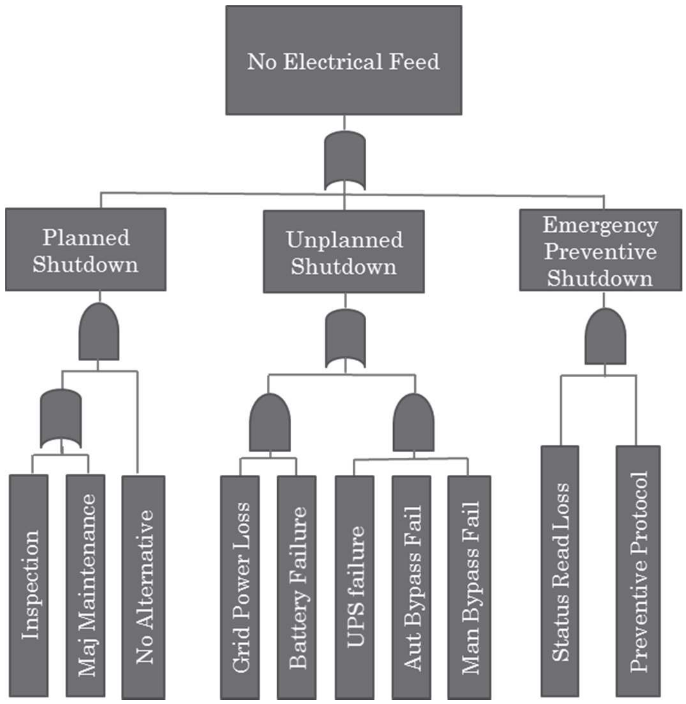


Figure 42: Real case downtime FTA

Similarly, using Appendix G the following is obtained as a breakdown FTA.

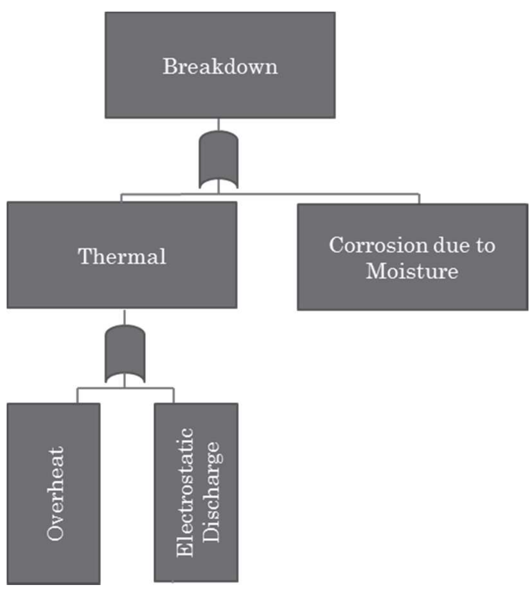


Figure 43: Real case breakdown FTA

The next step is to find data. Part of this information is of technical nature, used to populate the FTAs developed. Additionally, non-technical data is also be required in able to check if replacement is justifiable.

6.2.1 Data Collection

This section will focus on obtaining information for determining the non-replacement losses on this UPS unit case. The replacement condition information will be estimated (assumed) depending on the non-replacement results obtained.

Non-Technical Data

Gassco AS underwent an analysis of several of their systems recently. This was done by external agents and looked to determine which equipment required replacement (amongst other things) due to obsolescence, better alternatives, etc. The UPS units that are treated in this section were a part of this analysis. This, together with some other internal documents and estimates was the basis for obtaining the required non-technical data for this case.

Concept	Value	Units
Gas Transport per Compressor	**15**	Mill scm/day
Selling Price	**2**	NOK/scm
UPS Estimated Lifetime	**25**	Years
Investment Capital (per compressor)	**4.5**	Mill NOK
Cost of Capital	**5**	%
Loan Yearly Interest Rate	**2.8**	%
Tax Rate	**0**	%

Table 20: Real case non-technical data

The data shown in Table 20 is already enough to calculate the right side of the model inequality. Additionally on the left side. Fc_R can also be obtained according to the loan interest rate in it. The rest of the elements in the left side either have some technical dependencies or require a more detailed search of information.

Technical Data

Of the remaining information to be obtained, some of it is related to the developed FTAs and thus Pc_N, Ec_N and Lc_N. The rest is independent of these FTAs and linked to Oc_N and Rc_N. These last two could not be obtained shortly because they are registered in an internal software system that assigns certain costs to certain units. This same system also includes data that could be used to obtain the downtime and breakdown information required. There is, however, an important limitation. The classification of the available information is not compatible with the developed FTAs. It is not split in a manner in which the values of their blocks can be determined. An alternative has to be used.

A suitable option is to use the diagram from Figure 38 to elaborate a RBD. The calculations for downtime could then be obtained by following the procedure explained in 2.3.3.

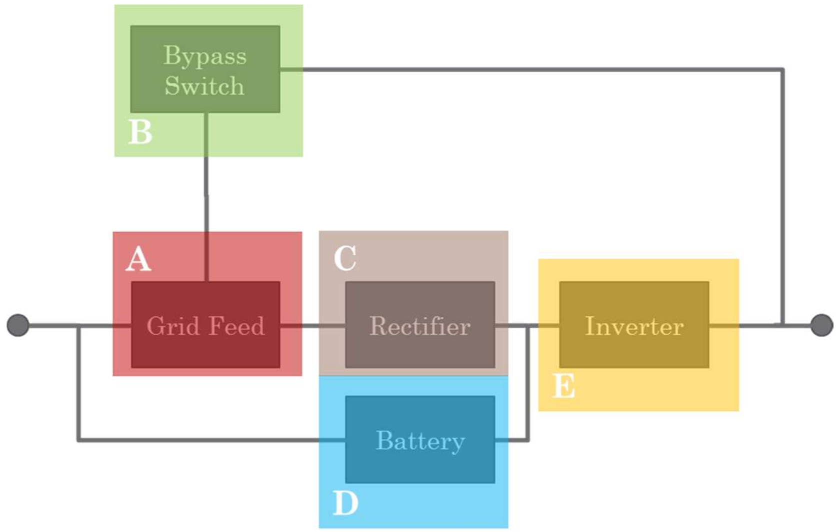


Figure 44: Single UPS RBD

Notice Figure 44 is entirely based off of Figure 38. It will now be attempted to use this RBD in able to get the downtime and thus Pc_N. Nevertheless, this is still dependent on the information available. The compressing units for this case are part of two substations tagged as "A52B" and "A53B". Each of these substations has two UPSs (labelled "α" and "β"), they are identical. Nonetheless, only one UPS per station is directly assigned to critical support elements for the compressor. Even if only two of these UPSs are of interest, the failure data available for the other two is also valid since they are identical. Thus, information will be obtained for the four of them and the results then adjusted to a "per UPS" basis.

Appendix J is a synthetized and processed version of the raw data obtained for the four UPS found in substations A52B and A53B. A sample range of 18 years is available. The rows and columns of main interest are highlighted. There are five failures that were important enough to cause a breakdown. These will be deemed as the only ones with the potential to lead to downtime. Breakdowns combined in the manner can lead to such condition. They will be classified into the blocks of in Figure 44's RBD. It is important to note that a single breakdown may affect more than one block. According to the description of these events, the number of breakdowns for the individual components can be found.

Appendix K includes all maintenance costs involved in substations A52B and A53B (for both UPSs in each case, thus four total). From this information, not only can Ec_N and Lc_N be found, but also

Oc_N and Rc_N. This is because it has costs on expenditure other than just breakdown repairs. Thus, non-breakdown expenses can be classified as either Oc_N or Rc_N.

6.2.2 Data Processing

The five breakdowns found in the information obtained are classified by substation and UPS. Then, according to the details provided in the data, the affected components for each breakdown are determined.

Substation	UPS	Battery	Bypass	Rectifier	Inverter
A52B	α	X			
A52B	β		X	X	X
A53B	α		X		
A53B	β	X	X	X	X
A53B	β	X	X	X	X
		3	4	3	3

Table 21: Overview of UPS components affected by breakdowns

Table 21, shows each of the five breakdowns and the UPS components each affected. Notice that in three of the five cases, multiple components were affected (all in two breakdowns). It is important to keep in mind that these numbers have to be divided by four in able to do an individual UPS analysis. While this is a good starting point, this information still has to be processed.

In the information available, every breakdown has a date of notification and one of technical completion. The difference between these two can be considered to be the MTTR. Considering an eighteen year period is available, the MTTF can be calculated and thus the MTBF and Failure rate (λ). If MTTR and MTBF are at ones disposal, the availability and unavailability of the components can also be calculated.

Section	MTTR [h]	MTTF [h]	MTBF [h]	Fail Rate λ [h-1]	No. of Breakdowns	Avg. Unavailability	Avg. Availability
Battery	184.0	210056	210240	4.76E-06	0.75	0.09%	**99.91%**
Bypass	468.0	157212	157680	6.34E-06	1	0.30%	**99.70%**
Rectifier	112.0	210128	210240	4.76E-06	0.75	0.05%	**99.95%**
Inverter	112.0	210128	210240	4.76E-06	0.75	0.05%	**99.95%**
Source	From Data	Calculation	Calculation	Calculation	From Data	Calculation	Calculation
Formula	Mean MTTR	MTBF - MTTR	$\frac{1}{\lambda}$	$\frac{\#Failures}{Sample\ Time}$	Total breakdowns/4	$\frac{MTTR}{MTBF}$	1-Unavailability

Table 22: Real case downtime processed data for non-replacement case

Table 22 summarizes the results of processing the data pertaining downtime for this case. Notice how (1), (2) & (4) are used in the calculations. The Failure rate is obtained by using the available 18 years of sample time. Nonetheless, this still needs to be eventually translated into Pc_N. For that, grid availability data is required. Due to it not being accurately measured, theoretical reliability numbers are obtained through (M. K. Rahmat, S. Jovanovic, & K. L. Lo, 2010) and (Mohd Khairil Rahmat, Slobodan Jovanovic, & Kwok Lun Lo, 2010).

Section	MTTR [h]	MTTF [h]	MTBF [h]	Fail Rate λ [h-1]	No. of Breakdowns	Avg. Unavailability	Avg. Availability
Grid Feed	0.6	2221.6	2222	4.50E-04	NA	0.03%	99.973%
Source	Estimate	Calculation	Calculation	Literature		Calculation	Calculation
Formula		MTBF - MTTR	$\frac{1}{\lambda}$	Rahmat 2010		$\frac{MTTR}{MTBF}$	1-Unavailability

Table 23: Real case grid feed availability

Afterwards, a way of interrelating the independent availability of components is necessary. This can be done with the help of the RBD shown in Figure 44. Using (5) and (6), the RBD can be further broken down and the system availability obtained.

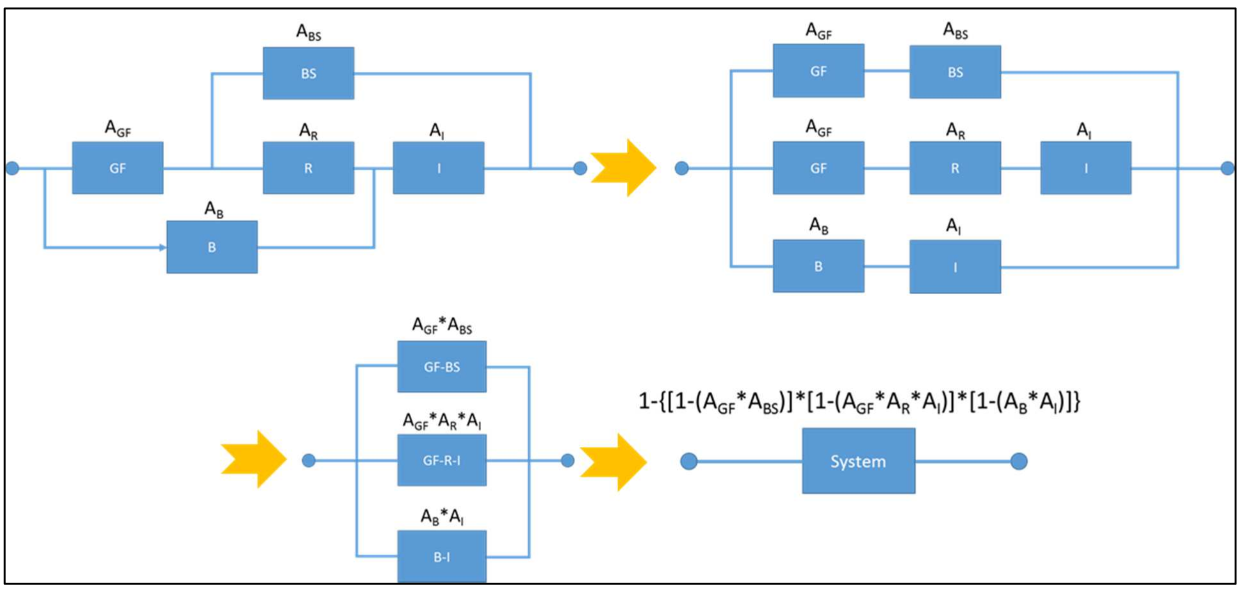


Figure 45: Real case RBD calculation process

According to Figure 45, the system has an availability of 99.99999939%. The downtime state is then the difference between 1 and the availability:

Downtime (Non-Replacement) = DT_N = **0.0000006802%**

This number combined with the transport and price information provided in Table 20 should be enough to provide Pc_N.

For the rest of the left side variables, Appendix K is used. The breakdowns previously identified are cross-referenced and their spare part and labor repair costs determined. According to their description, some expenses are deemed to be "reactive" due to their immediate "emergency-like" nature. Expenses that are neither related to breakdowns nor reactive are considered to be overly costs.

	Reactive	Standard		
Breakdown	174303.54	44131.00	**218434.54**	EcN + LcN
Non-Breakdown	**140479.29**	**1642050.52**	OcN	
	RcN			

Table 24: Real case maintenance cost assignments

6.2.3 Constant Deltas Calculation

Non-Replacement

Pc_N can be determined with the system downtime, gas transport rate and gas selling price. All of these are available. It should be kept in mind that Pc_N is required on a "per year" and "per UPS" basis.

$$Pc_N = DT_N * (Transport\ Rate) * (Price)$$

$$Pc_N = 6.802 * 10^{-9} * \frac{1.5 * 10^7 scm}{day} * \frac{2\ NOK}{scm} * \frac{365\ day}{year} * \frac{1\ mill\ NOK}{1 * 10^6\ NOK}$$

$$\boldsymbol{Pc_N} = 6.7 * 10^{-5}\ {}^{mill\ NOK}/_{year}$$

The rest of the variables are obtained by using Table 24. The available data makes no distinction between expenditure assigned to spare parts and labor repair. Thus, the Ec_N and Lc_N costs will be considered to be equal (50% of the $Ec_N + Lc_N$ costs for each).

Using million NOK, and standardizing the figures to per year & per UPS unit base, the following is obtained (including the previously calculated Pc_N).

Variable	Loss (mill NOK/year)
Pc_N	0.000067
Ec_N	0.001525
Lc_N	0.001525
Oc_N	0.022800
Rc_N	0.001950

Table 25: Real case non-replacement losses

Table 25 includes all the non-replacement losses. Fc_N is zero since no investment is made in this case and thus no interests paid. Unlike the mock case, these are much lower figures. In the case of EcN and LcN, these losses can be further broken down into breakdowns/year and avg. cost/breakdown.

$$\frac{Breakdowns}{year} = BD_N = \frac{Total\ Breakdowns}{Sample\ years} = \frac{5}{18} = 0.2778\ ^{breakdowns}/_{year}$$

$$\frac{Avg.Spare\ Cost}{Breakdown} = SPC_N = \frac{Avg.Labor\ Repair\ Cost}{Breakdown} = LRC_N = \frac{Ec_N}{BD_N} = \frac{Lc_N}{BD_N}$$

$$SPC_N = LRC_N = \frac{0.001525\ mill\ NOK}{year} * \frac{year}{0.2778\ breakdowns}$$

$$= 0.00549\ ^{mill\ NOK}/_{breakdown}$$

Obtaining BD_N, SPC_N and LRC_N now gives the results more of the feel originally expected by the use of the guideline FTAs proposed by this project.

Replacement

In able to calculate the deltas, now the replacement parameters must be determined. Most of these will be based on the non-replacement figures. FcR, however, is independent of the non-replacement case and can be calculated by using (29).

Fc_R = 0.0727 mill NOK

Pc_R depends on the expected failure rate of the UPS components. A similar approach to the one found in Table 22 can be taken. Nonetheless, a lower number of breakdowns for the same sample period would be expected, since the equipment would be new. It seems sensitive to expect around 60% of the non-replacement breakdowns. In able to keep the same reference point, the following still considers an 18 year sample period. The MTTRs will be considered to be the same as in the non-replacement case.

Section	MTTR [h]	MTTF [h]	MTBF [h]	Fail Rate λ [h-1]	No. of Breakdowns	Avg. Unavailability	Avg. Availability
Battery	184.0	394016	394200	2.54E-06	0.4	0.047%	99.95%
Bypass	468.0	262332	262800	3.81E-06	0.6	0.178%	99.82%
Rectifier	112.0	394088	394200	2.54E-06	0.4	0.028%	99.97%
Inverter	112.0	394088	394200	2.54E-06	0.4	0.028%	99.97%
Source	From Data	Calculation	Calculation	Calculation	Assumption	Calculation	Calculation
Formula	Mean MTTR	MTBF - MTTR	$\frac{1}{\lambda}$	$\frac{\#Failures}{Sample\ Time}$	Total breakdowns/4	$\frac{MTTR}{MTBF}$	1-Unavailability

Table 26: Real case downtime data for replacement case

The availability of all components rose slightly. The grid feed won't be affected by a UPS replacement and the interrelations between components will remain the same. Therefore, Table 23 and Figure 45 are also valid for the replacement case. Following the same process as for non-replacement the downtime is found.

Downtime (Replacement) = DT_R = **0.000000129%**

The gas transport rate and price will remain unaffected.

$$Pc_R = DT_R * (Transport\ Rate) * (Price)$$

$$Pc_R = 1.29 * 10^{-9} * \frac{1.5 * 10^7 scm}{day} * \frac{2\ NOK}{scm} * \frac{365\ day}{year} * \frac{1\ mill\ NOK}{1 * 10^6\ NOK}$$

$$\boldsymbol{Pc_R} = 1.41 * 10^{-5}\ {mill\ NOK}/{year}$$

Regarding EcR and LcR, they will still be considered to be equal. However, BDR, SPCR and LRCR will be considered to be lower. This is because new equipment is expected to breakdown less often. It also requires less money to be fixed since spare parts are readily available and no special repair labor will be required. Thus, these variables will change into the following.

Variable	Non-Replacement	Replacement
BD	0.2778	0.0200
SPC	0.0055	0.0050
LRC	0.0055	0.0050

Table 27: Ec & Lc dependent variable changes

$$Ec_R = BD_R * SPC_R = 0.02 * 0.005 = 0.001$$

$$Lc_R = BD_R * LRC_R = 0.02 * 0.005 = 0.001$$

There are no particular reasons to believe either Oc_R or Rc_R will decrease with replacement and thus they will be considered to remain unchanged.

Variable	Loss (mill NOK/year)
Pc_R	0.000014
Ec_R	0.001000
Lc_R	0.001000
Oc_R	0.022800
Rc_R	0.001950
Fc_R	0.072700

Table 28: Real case replacement losses

Results

With every variable known, (27) can be calculated.

$$[(\Delta Pc' + \Delta Ec' + \Delta Lc' + \Delta Fc' + \Delta Oc' + \ \Delta Rc')] > \frac{\left[\frac{IC_R}{n}\right] * \left[1 + CoC * \left(\frac{n-1}{2}\right) - TR\right]}{(1 - TR)}$$

The left side becomes:

$$[(6.7 - 1.4) * 10^{-5} + (1.525 - 1.0) * 10^{-3} + (1.525 - 1.0) * 10^{-3} + (0 - 7.27) * 10^{-2} + (2.28 - 2.28) * 10^{-2} + \ (1.95 - 1.95) * 10^{-3})] = \mathbf{-7.165 * 10^{-2}}$$

The right side is then:

$$\frac{\left[\frac{4.5}{25}\right] * \left[1 + 0.05 * \left(\frac{25-1}{2}\right) - 0\right]}{(1 - 0)} = 0.288$$

$$\boxed{\mathbf{-0.07165 > 0.288}}$$

The left side is nowhere close to satisfying the inequality. It is actually negative, which means the money required to pay the interests for the investment loan is greater than the loss gap between non-replacement and replacement cases.

6.2.4 Minimum/Maximum Required Parameter Values

Analogous to the mock case, with the help of the RAT, the minimum or maximum parameter values in able to fulfill the inequality will be sought. Once again, for consistence purposes, (28) will be used instead of (27). This yields the following values:

$$\boxed{\mathbf{-1.7912 > 7.2}}$$

These numbers are the ones found by using (27) but multiplied by 25 (lifetime of new equipment). By using the software tool, a similar table in relation to the mock case is obtained. For this particular case, the choke time state is not included since it is not present.

Changing Parameter	Case	Original Value	Required Value
Downtime State	Non-Replacement	0.00000061%	Min. 0.003285%
	Replacement	0.00000013%	NA
Number of Breakdowns	Non-Replacement	0.27778 per year	Min. 33.03 per year
	Replacement	0.20000 per year	NA
Spare Part Avg. Cost	Non-Replacement	0.0055 Mill NOK/Fail	Min 1.3 Mill NOK/F
	Replacement	0.0050 Mill NOK/Fail	NA
Labor Repair Avg. Cost	Non-Replacement	0.0055 Mill NOK/Fail	Min 1.3 Mill NOK/F
	Replacement	0.0050 Mill NOK/Fail	NA
Loan Interest Rate	Replacement	2.8% per year	NA
Overly Costs	Non-Replacement	0.023 Mill NOK/year	Min. 0.38 Mill NOK/y
	Replacement	0.023 Mill NOK/year	NA
Reactive Costs	Non-Replacement	0.002 Mill NOK/year	Min. 0.36 Mill NOK/y
	Replacement	0.002 Mill NOK/year	NA
n (Lifetime)	General	25 years	>50*
IC	General	4.5 Mill NOK	Max. 0.013 Mill NOK
CoC	General	5%	NA
TR	General	0%	NA

Table 29: Real case minimum/maximum required parameter values (constant deltas)

Table 29 shows that the changing of any of the replacement variables is not enough to fulfill the inequality, even if they go all the way down to zero. The minimum required lifetime is larger than fifty years and the RAT can only handle 50 years lifetime maximum. Nonetheless, it is clear this number would have to be very large, thus making it unrealistic. The minimum for the non-replacement variables is extreme compared to the original ones. This is a good indicator that even with changing deltas, justifying this replacement will likely be extremely hard. Even then, such case will be analyzed.

6.2.5 Changing deltas Analysis

In the same manner as in the mock case, the RAT will be used to determine the required growth rate of each parameter to fulfill the inequality with every other parameter remaining unchanged. This will be used to have a better idea of which of them can affect the end result in a greater manner in a real changing delta scenario. It shall be noted that negative growth is not considered to be a possibility.

Changing Parameter	Case	Original Value	Required Growth
Downtime State	Non-Replacement	0.205%	Min. 53.8% yearly
	Replacement	0.140%	NA
Number of Breakdowns	Non-Replacement	3 per year	Min. 34% yearly
	Replacement	2 per year	NA
Spare Part Avg. Cost	Non-Replacement	2 Mill NOK/Fail	Min. 34% yearly
	Replacement	3 Mill NOK/Fail	NA
Labor Repair Avg. Cost	Non-Replacement	2 Mill NOK/Fail	Min. 34% yearly
	Replacement	2.5 Mill NOK/Fail	NA
Loan Interest Rate	Replacement	2.8% per year	NA
Overly Costs	Non-Replacement	16 Mill NOK/year	Min. 18.2% yearly
	Replacement	18 Mill NOK/year	NA
Reactive Costs	Non-Replacement	2 Mill NOK/year	Min 32.51% yearly
	Replacement	0.5 Mill NOK/year	NA

Table 30: Real case changing delta required growth

The required growths shown in Table 30 have to be constant for every year. This means that their cumulative nature makes the growth exponential. Please refer to Appendix L for graphs showing the sensitivity of the model to the yearly growth of the different parameters involved. These large growths are very improbable to happen, thus a more likely scenario is to have not only one parameter growing but several of them.

The RAT was utilized to evaluate different growth rate scenarios that could fulfill the inequality. It was noted that under the two the following conditions this could be accomplished.

1. Set all non-replacement yearly growths to 13.5%
2. Set all replacement yearly growths to 3.5%

Year	PcN	PcR	EcN	EcR	LcN	LcR	FcN	FcR	OcN	OcR	RcN	RcR	ΣXN	ΣXR	Gap (ΣXN-ΣXR)
1	0.00007	0.00001	0.002	0.001	0.002	0.001	0	0.073	0.023	0.023	0.002	0.002	0.03	0.10	-0.07
2	0.00008	0.00001	0.002	0.001	0.002	0.001	0	0.073	0.026	0.024	0.002	0.002	0.03	0.10	-0.07
3	0.00009	0.00002	0.003	0.001	0.003	0.001	0	0.073	0.029	0.024	0.003	0.002	0.04	0.10	-0.06
4	0.00010	0.00002	0.003	0.001	0.003	0.001	0	0.073	0.033	0.025	0.003	0.002	0.04	0.10	-0.06
5	0.00011	0.00002	0.004	0.001	0.004	0.001	0	0.073	0.038	0.026	0.003	0.002	0.05	0.10	-0.05
6	0.00013	0.00002	0.005	0.001	0.005	0.001	0	0.073	0.043	0.027	0.004	0.002	0.06	0.10	-0.05
7	0.00014	0.00002	0.007	0.002	0.007	0.002	0	0.073	0.049	0.028	0.004	0.002	0.07	0.11	-0.04
8	0.00016	0.00002	0.009	0.002	0.009	0.002	0	0.073	0.055	0.029	0.005	0.003	0.08	0.11	-0.03
9	0.00018	0.00002	0.012	0.002	0.012	0.002	0	0.073	0.063	0.030	0.005	0.003	0.09	0.11	-0.02
10	0.00021	0.00002	0.015	0.002	0.015	0.002	0	0.073	0.071	0.031	0.006	0.003	0.11	0.11	0.00
11	0.00024	0.00002	0.019	0.002	0.019	0.002	0	0.073	0.081	0.032	0.007	0.003	0.13	0.11	0.01
12	0.00027	0.00002	0.025	0.002	0.025	0.002	0	0.073	0.092	0.033	0.008	0.003	0.15	0.11	0.04
13	0.00030	0.00002	0.032	0.002	0.032	0.002	0	0.073	0.104	0.034	0.009	0.003	0.18	0.11	0.06
14	0.00035	0.00002	0.041	0.002	0.041	0.002	0	0.073	0.118	0.036	0.010	0.003	0.21	0.12	0.09
15	0.00039	0.00002	0.053	0.003	0.053	0.003	0	0.073	0.134	0.037	0.011	0.003	0.25	0.12	0.13
16	0.00045	0.00002	0.068	0.003	0.068	0.003	0	0.073	0.152	0.038	0.013	0.003	0.30	0.12	0.18
17	0.00051	0.00002	0.088	0.003	0.088	0.003	0	0.073	0.173	0.040	0.015	0.003	0.36	0.12	0.24
18	0.00057	0.00003	0.113	0.003	0.113	0.003	0	0.073	0.196	0.041	0.017	0.004	0.44	0.12	0.32
19	0.00065	0.00003	0.146	0.003	0.146	0.003	0	0.073	0.223	0.042	0.019	0.004	0.53	0.13	0.41
20	0.00074	0.00003	0.188	0.004	0.188	0.004	0	0.073	0.253	0.044	0.022	0.004	0.65	0.13	0.52
21	0.00084	0.00003	0.242	0.004	0.242	0.004	0	0.073	0.287	0.045	0.025	0.004	0.80	0.13	0.67
22	0.00095	0.00003	0.311	0.004	0.311	0.004	0	0.073	0.326	0.047	0.028	0.004	0.98	0.13	0.84
23	0.00108	0.00003	0.401	0.005	0.401	0.005	0	0.073	0.370	0.049	0.032	0.004	1.20	0.13	1.07
24	0.00123	0.00003	0.517	0.005	0.517	0.005	0	0.073	0.420	0.050	0.036	0.004	1.49	0.14	1.35
25	0.00139	0.00003	0.665	0.005	0.665	0.005	0	0.073	0.476	0.052	0.041	0.005	1.85	0.14	1.71
															7.20

Table 31: Real case changing deltas for inequality fulfillment summary

Table 31 shows the values that the left side parameters will take in able to equal 7.2 mill NOK, which is the same as for the right side of the inequality, thus yielding the replacement option sound. From it one can note that the main contributors towards the fulfillment of the inequality are Ec_N, Lc_N and Oc_N. It is important to note that both Ec_N and Lc_N are subject to two increasing parameters. One is BD_N and the second is SPC_N and LRC_N respectively.

Parameter	Initial Value (year 1)	Final Value (year 25)	Times-fold Increase
Ec_N	0.002	0.665	332
Lc_N	0.002	0.665	332
Oc_N	0.023	0.476	21

Table 32: Real case critical parameter time-fold required increase

Table 32 shows a comparison between the initial and final values of the three main critical parameters. It seems hard to imagine a case in which the values would increase that much. It seems like replacement does not look convenient in this case. Figure 46 shows the yearly gap previously presented in the last column of Table 31 in a graphical manner. Notice how the area below the curves in Figure 46 is either the sum of ΣX_N or ΣX_R for all years of the analysis. If data could somehow be modeled analytically with an equation as a function of time, its integration would give the ΣX_x.

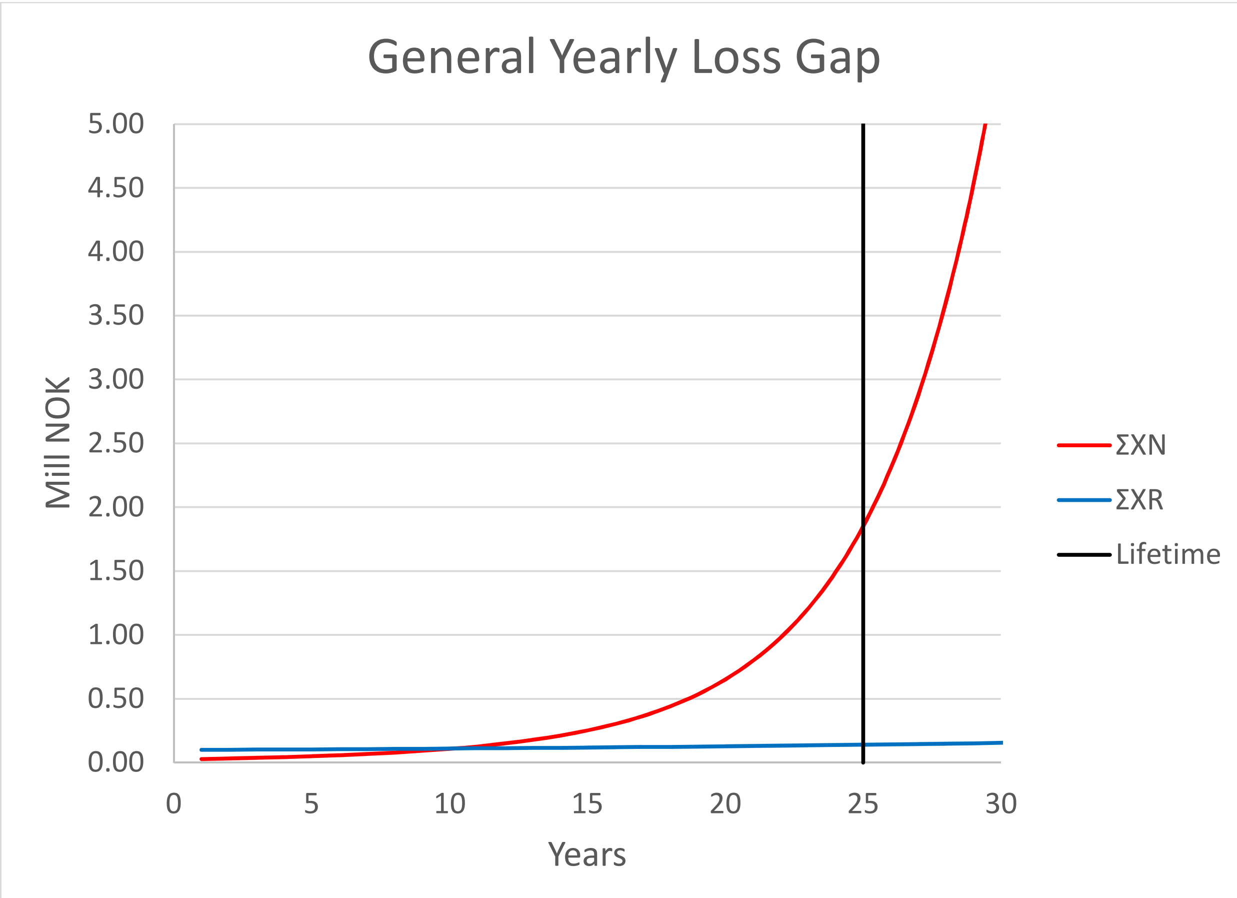


Figure 46: Real case yearly gap with changing deltas

6.3 Result Evaluation

The extremely low downtime presented in this case makes Pc almost irrelevant. Even at very high yearly growths, its initial value is so low, that it is dwarfed in relation to other parameters. Nonetheless, one needs to keep in mind that each day, thirty million NOK are generated by each compressing unit due to their daily gas transportation. This is 1.25 million NOK per hour which means that six downtime hours are enough to surpass the 7.2 million NOK on the right side of the equation. This does not look likely, but when it comes to production losses, they can pile up rather quickly under catastrophic failures.

Similar to Pc, Rc also takes a back seat to the critical parameters. Emergency spending can sky rocket, however, if the non-replacement conditions lead to major failures, spares are scarce and labor repair is expensive. Another possibility is that a penalty is given by an external agent due to operating with obsolete equipment in case that is not allowed. Even then, it seems unlikely that Rc would play the critical role in satisfying the inequality.

Ec, Lc and Oc are the most important parameters for this case. Nonetheless, the growth required for each of the variables they depend on (for the non-replacement case) simply seems too large. The data obtained from Gassco AS combines these three parameters plus Rc and can be divided in a yearly basis. This can be useful to identify if there is a clear rising tendency in losses.

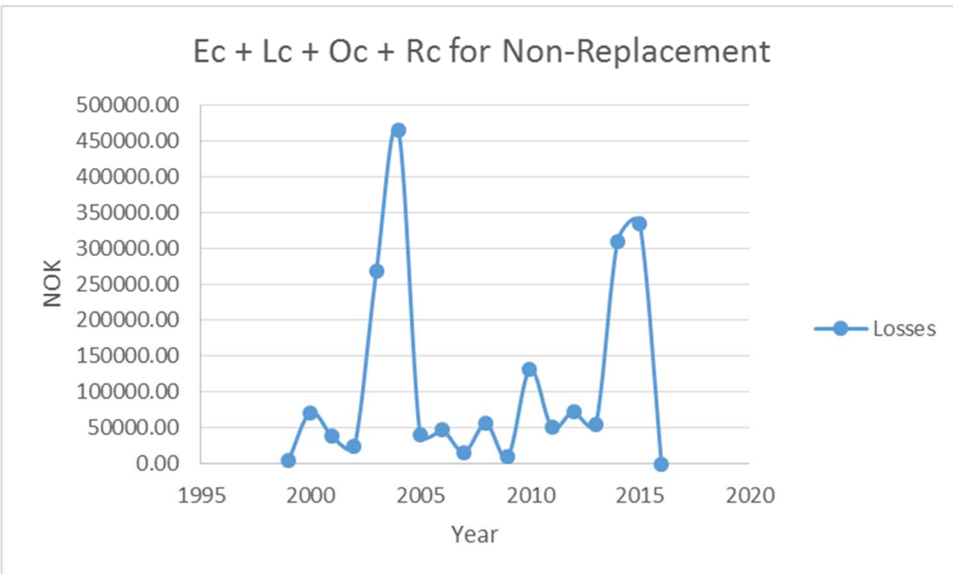


Figure 47: UPS losses tendency through sample period

Unfortunately, there is no clear indication of a steady increase in these losses. That leaves the replacement option as a less attractive choice.

There are several things that can be done in able to make this real case study more precise. For instance, the downtime estimates can be better calculated using reliability figures of the specific UPS model that would replace the new one. Additionally, one could extend the scope of the overly costs. For now, they only consider maintenance related expenditure on the UPSs that is neither breakdown nor reactive related. Continuous monitoring spending, including personnel could also be a part of this. Surely once this is obtained it would have to be analyzed to determine if those costs would increase or decrease after replacement.

Overall, according to the methodology suggested in this project, the replacement of the UPS units would not be suggested to Gassco AS. The conditions under which such investment is justified seem to be extremely improbable. Even then, it is essential to keep in mind that the reach of this project's methodology is limited. The UPS case was evaluated by the company before this thesis commenced, and the decision was made for replacement. Some factors weighed in for that decision include HSE considerations that the analysis of this model fails to include. For example, this model does not assign a potential loss differential dependent on the likelihood of someone to get injured by a malfunction in the UPS units. This is a clear reason for the lack of consistency between the two methods.

7 Practical Suggestions

While the proposed model seems to be at least a good step towards justifying equipment replacement financially, there are several aspects in which this process can be better accomplished. Across the duration of this project, the methodology suffered important changes until arriving to the form in which it is presented. Any further modifications are out of the scope of this thesis. Nonetheless, it is important to bring them up in able to be the basis for any future efforts in this matter.

7.1 Methodology Improvements

The first part of the process that clearly needs to be assessed is the use of the FTA guidelines for obtaining the technical parameters. It was not of any help for the real case involving the UPS units and it looks like it would be tough for it to have an important contribution in other cases. The mere nature of reliability engineering makes it so that it is virtually impossible to not do case to case assessments. Since this project had the objective of having a methodology that could be general enough for most cases, the FTA guidelines were attempted, but it looks like their use is not imperative.

Another thing that could make the methodology smoother and contribute in having a more consistent analysis is the use of (28) as the sole assessment inequality. This is because it also has the capacity of handling non-changing deltas. (27) Can still be used as a reference to get an idea of the yearly impact, however, it is easier to just divide (28) by the lifetime. In the end, these inequalities present cashflows and thus the one with the capacity to consider multiple years seems more intuitive.

Lastly, there has to be a much more thorough analysis to determine what yearly growth value to use for every parameter. This was neither done for the mock nor the real case, however, it should be considered as the best alternative for determining if replacement is financially advisable. In able to do this, particularly for the technical parameters, the involvement of experts in equipment reliability would be advisable. It would be dangerous to simply assume values without proper reasoning behind it.

7.2 Obtaining Data

The analysis of the UPS unit case had one main challenge, information. Not only was it challenging to obtain the data, but it was not possible to have it classified in a manner that made it more convenient for the use of the desired methodology. This is particularly the case for anything related to the technical parameters. It was troublesome identifying which faults to identify as actual potential causes of breakdown or downtime. Other than that, it was also strenuous to identify which particular subcomponents were affected on every case. Thus, certain measures could be taken in able to add value to the data collection process. The following is a list of potential aspects that can contribute to obtaining better maintenance information to be used by this model.

a) Mark each fault as either a planned or corrective action
b) Identify the critical subcomponents of a system and mark the ones that "go down" for each fault
c) Divide expenses into spare part and labor repair costs
d) Explicitly indicate the MTTR for every failure

Point a) is important in able to determine if these types of expenses are to be either Ec & Lc or simply Oc. This is because any planned maintenance automatically would be classified as Oc. Knowing which subcomponents get affected by specific failures is imperative for the determination of system downtime and breakdowns. That is why b) is desired. In the UPS case, this would have meant that every failure would have to mark each subcomponent (battery, bypass, inverter or rectifier) in case it were affected. Dividing expenses into Ec and Lc is important in able to determine which one of these has a larger contribution and for better prognostics regarding the replacement scenarios. Point d) might be the most important one. For the UPS case, the difference between the technical completion date and the initial failure report date was used as MTTR. However, this might not necessarily be the case. This is a critical piece of information and it would be extremely beneficial to have it directly.

7.3 Step by Step Summary

The following is an effort to summarize the steps required to follow for this methodology. It shall be used as a general guideline. It does not necessarily present the best alternative for all cases, but it will work every time.

Obtain the non-technical general information (Cost of investment, cost of capital, tax rate, loan interest rate & investment lifetime).

1. Elaborate a RBD of the system to be analyzed.
2. Obtain historical reliability information on all subcomponents included in the RBD.
3. Classify and process this information in able to obtain downtime, choke state and breakdowns.
4. Retrieve overly and reactive costs.
5. Estimate or calculate the losses for the replacement scenario.
6. Use RAT to determine if the inequality is satisfied with no yearly increasing
7. Find the minimum and maximum values for each parameter to fulfill the inequality.
8. Find the minimum or maximum yearly growth percentage for each parameter in able to fulfill the inequality.
9. Input the most likely growth rates for each parameter in the RAT, check if the inequality is satisfied.
10. Use the findings to determine if the investment should be made.

7.4 RAT Use and Limitations

The RAT can be a very convenient tool to use as an integral part of this methodology. Nonetheless, it is crucial to point out some of its limitations in able to avoid confusion. First of all, this tool has no capacity of using nominal values. That means that every value used or shown is in present value. For example, if a 5,000 NOK expense is shown to happen five years from now, it means that regardless of its future nominal value (likely higher than 5000 NOK), its present value would be 5,000. This is important, because it would perhaps be good to see how using different discount rates could affect the analysis, however this is not possible.

Regarding changing deltas, it is also imperative to be reminded that the tool can only handle constant growths. That is, the yearly growth percentage cannot change from year to year. If it is 3% on the first year, it cannot take a different value for any of the remaining years with the tool. This is perhaps not realistic, as for certain equipment, it might be possible that it starts with a low yearly growth percentage and it eventually rises significantly.

Finally, the sensitivity analysis presented in the RAT considers only one variable at a time. That means that an analysis of change in multiple variables cannot be done automatically. It is however possible to do so manually. This is a strong limitation since in most cases, changes in more than just one parameter will be what takes the inequality from fulfillment to non-fulfillment and vice-versa.

8 Conclusion

Developing a fact-based methodology to help Gassco AS financially support equipment replacement decisions was the objective of this project. It was accomplished to a fairly high degree. While a universal and infallible solution was not reached, the model this project proposes points the company in the right direction. With additional efforts, a much better end result can be achieved.

The literary survey of this project found out that discounted cashflow techniques are probably the most popular way of determining if an equipment replacement investment should be made. However, the technical aspects pertaining reliability engineering cannot be directly introduced into discounted cashflows. One way to include these technical features is to modify existing DCF methodologies. A clear example is the CoUr process. It has very high intuitive value, since it gives the user a result based on the amount of money one loses due to unreliabilities in the system analyzed. It is also technically sound; it recommends the use of RBDs and indicates which parameters one must focus on. While the basis of DCF is strong enough to assess projects, it fails to consider certain long term priorities, primarily shareholder value creation. The EVA methodology is a solution to this issue; it accounts for the profits that one is expected to make relative to the invested capital one has and the shareholders' expected rate of return.

After analyzing the popular techniques used to help decide if ageing equipment should be replaced or not, it was easier to understand what originated the need for this project. There are many ways in which one might try to find out the answer to this question, but none seems to include all the pertinent elements. Moreover, going through the process of obtaining reliability results for the system to be analyzed can be exhaustive. Therefore, this thesis project attempted to come up with a combined version of two of the more solid models found through the literary survey (CoUr and EVA). Additionally, a general set of FTAs would be developed in able to help with the equipment reliability related part of the analysis.

A significant amount of mathematical deductions were required in able to arrive to a final expression that could be used for this project's purposes. The result of these efforts is (28). This expression is an inequality that once fulfilled, indicated a replacement investment is financially justifiable. Throughout this thesis, there has been a clear distinction between the two sides of (28). The right one is linked to the investment, its amount required and lifetime as well as some internal company characteristics like cost of capital and tax rates. The left side includes loan interest payments, non-breakdown operational costs and technical parameters. In able to aid in obtaining the technical parameters, three different FTA guidelines were developed: downtime, choke state and breakdown. The idea behind these was to be used as starting points towards developing case-to-case FTAs.

Before testing the developed methodology with a real case, an imaginary mock case was constructed. The purpose of this fictional scenario was to discover potential problems with the methodology and to get a feel for the steps required to be followed. This stage in the project also triggered the development of a spread sheet aid tool (RAT) that ultimately became a cornerstone for the proposed model. Before this mock case was completed, the thesis had settled to analyze the replacement possibility with constant deltas as in (27). After noticing that the final decision can be different if one considers changing deltas, the focus of the project shifted into making sure (28) could be used as the most important inequality. Additionally, sensitivity analysis capabilities were added to the RAT for a better evaluation of the mock case. This phase was crucial for the project, nonetheless, it included some severe technical simplifications. This fact led to questioning the value of the FTA guidelines previously produced.

Once a mock case proved the proposed methodology could be of important help, the quest for analyzing a real case took part. A UPS unit replacement dilemma was selected for analysis. The most important challenge for this chapter circled around information. Initially, simply obtaining relevant information was demanding. Once data was obtained, processing it was an additional concern. Information had to be adapted in able to be useful within the proposed method. Several assumptions were made, and the nature of the faults obtained were not entirely clear. As suspected, the use of the FTA guidelines was not too fruitful. Nonetheless, an RBD was easily constructed and once data was processed, it was populated. The initial results for this case clearly indicated that replacement was not economically justifiable. Justifiable scenarios were ran with the help of the RAT in able to determine if one of them could be likely. Even then, it did not seem probable to have a situation in which the replacement of the UPS units was financially sound. This case was selected because it had been recently assessed. Due to obsolescence, the decision was made to replace the UPS units. That decision included safety and compliance factors that the model in this thesis failed to account for, thus the difference in conclusions between the two analyses.

After having completed both the mock and real cases, there were several current practices that were identified as areas of improvement. The most notorious one is related to maintenance information. 7.2 summarizes the most important aspects that could be worked on. Additionally, at this point a very general step by step list was made in able to follow the methodology proposed by this project. The availability of the RAT makes the applicability of the concepts this thesis presents much higher. Even when the technical parameters have a longer road to be obtained, the RAT makes it very convenient to change conditions at any point in time. It also allows for scenario and sensitivity analysis.

The main contribution of this project is the development of (28). The mathematical deductions required to arrive to it were carefully performed and it was quality proved. Most importantly, once it was tested, all the changes made in particular parameters moved the inequality in the expected direction. Not a single inconsistency was found. There are certain aspects that are not explicitly required by (28) and probably should. Financial considerations directly linked to the probability of human injury or life threat can be an important addition for the future. As of now, they can be included as a part of reactive costs, nonetheless, no particular method was presented nor developed in able to include them. Eventually, (28) could all be developed as a function of time. In this way, its integral over a specific period of time could give the result for the left side. The RAT is a good tool, but still not user friendly enough to be handled by anyone. It needs further work in able to reach its maximum potential. While this project is a step in the right direction, there still is a long path until a more reliable and usable tool is available.

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10 Appendixes

10.1 Appendix A

SMMT — **FAILURE MODE & EFFECTS ANALYSIS - DESIGN / ~~PROCESS~~**

FMEA NUMBER F375
SHEET 1 OF 12

PART OR ASSEMBLY NAME BOTTOM BRACKET (ENGINE MTG) SUPPLIERS PROFORM (RAW MAT'L)

PART OR ASSEMBLY NUMBER A 1234

DRAWING ISSUE A

AMENDMENTS	1	2	3	4	5	6	7	8	9	10
DATE	ORIGINAL									

FMEA COMMITTEE DESIGN, DEVELOPMENT, MANUFACTURING & QUALITY ENGINEERING

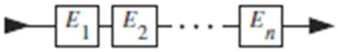
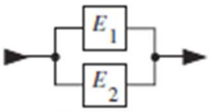
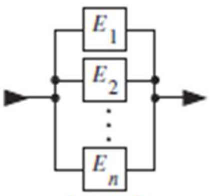
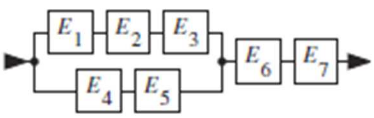
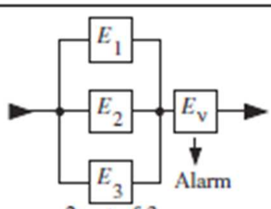
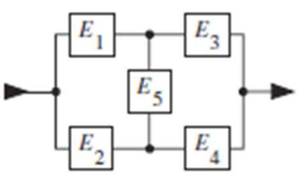
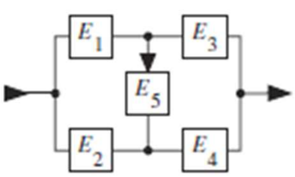
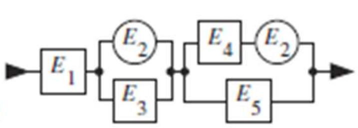
FMEA APPROVED DATE

NAME SIGNATURE

ITEM	PART No NAME ISSUE	FUNCTION OR PROCESS	FAILURE MODE	EFFECT OF FAILURE	CAUSE OF FAILURE	CURRENT CONTROLS	CURRENT STATUS				RECOMMENDED CORRECTIVE ACTION	ACTION BY	ACTION TAKEN	REVISED STATUS			
							OCC	SEV	DET	RPN				OCC	SEV	DET	RPN
11	A1234 BOTTOM BRACKET ISSUE A	TO PROVIDE ENGINE FRONT SUPPORT	BUCKLING FAILURE OF BRACKET VERTICAL WALLS	ENGINE DROP (COOLING FAN FOULS RADIATOR)	INCORRECTLY SPECIFIED MATERIAL THICKNESS	STRESS REPORT SR100 — TEST TO TR 150	3	8	3	72	TESTS TO BE CARRIED OUT TO TR 150 TO VERIFY STRESS REPORT SR 100	TEST / DEV'T	TESTS TO SPECIFIED LOAD PROVES ADEQUATE STATIC STRENGTH	2	8	2	32
12	-	-	-	-	SERVICE LOADS IN EXCESS OF DESIGN LOADS	NOT YET ESTABLISHED	4	8	9	288	VERIFICATION BY ROAD LOAD DATA / TEST BED REQUIRED & DRAWING CONTROLS ESTABLISHED	TEST / DEV'T	ROAD LOAD / TEST DATA CONFIRMS DESIGN LOADS ARE SATISFACTORY	1	8	3	[illegible]
13	-	-	CORROSION	GRADUAL LOSS OF STRENGTH LEADING TO STRUCTURAL FAILURE	INADEQUATE PROTECTIVE TREATMENT SPECIFIED	PROTECTIVE TREATMENT & SALT SPRAY TESTS ARE SPECIFIED (TR 150)	2	8	2	32	INSTALLATION TO BE REVIEWED AFTER ROAD & LABORATORY TESTS	VEHICLE PROVING	LABORATORY & ROAD TESTS WERE CARRIED OUT & NO CORROSION WAS EVIDENT	2	8	2	32
14	-	-	FATIGUE FAILURE (STRESS CONCENTRATION)	ENGINE DROP (COOLING FAN FOULS RADIATOR)	SPECIFIED BEND RADIUS TOO SMALL	FATIGUE TESTS ARE SPECIFIED IN TR 150	3	8	3	72	VERIFY BY SPECIFIED RIG TEST	TEST / DEV'T		2	8	2	32

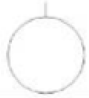
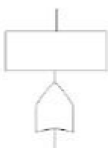
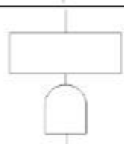
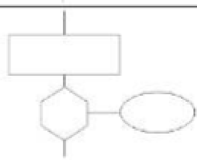
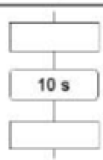
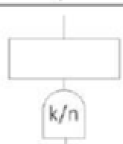
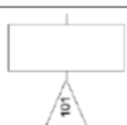
(Group, 2007)

10.2 Appendix B

Reliability Block Diagram	Reliability Function ($R_S = R_{S0}(t)$; $R_i = R_i(t)$, $R_i(0)=1$)	Remarks
 1	$R_S = R_i$	One -item structure, $\lambda(t)=\lambda \Rightarrow R_i(t)=e^{-\lambda_i t}$
 2	$R_S = \prod_{i=1}^{n} R_i$	Series structure, $\lambda_S(t)=\lambda_1(t)+\ldots+\lambda_n(t)$
 3	$R_S = R_1 + R_2 - R_1 R_2$	1 – out – of – 2 – redundancy, $R_1(t)=R_2(t)=e^{-\lambda t}$ $\Rightarrow R_S(t) = 2e^{-\lambda t} - e^{-2\lambda t}$
 4	$E_1 = \ldots = E_n = E$ $\rightarrow R_1 = \ldots = R_n = R$ $R_S = \sum_{i=k}^{n} \binom{n}{i} R^i (1-R)^{n-i}$	k - out - of - n redundancy for $k = 1$ $\Rightarrow R_S = 1-(1-R)^n$ see p. 44 for $E_1 \neq \ldots \neq E_n$
 5	$R_S = (R_1 R_2 R_3 + R_4 R_5 - R_1 R_2 R_3 R_4 R_5) R_6 R_7$	Series - parallel structure
 6	$E_1 = E_2 = E_3 = E$ $\rightarrow R_1 = R_2 = R_3 = R$ $R_S = (3R^2 - 2R^3) R_v$	Majority redundancy, general case $(n+1)$ – out – of – $(2n+1)$, $n = 1, 2, \ldots$
 7	$R_S = R_5 (R_1 + R_2 - R_1 R_2) \cdot (R_3 + R_4 - R_3 R_4) + (1 - R_5) \cdot (R_1 R_3 + R_2 R_4 - R_1 R_2 R_3 R_4)$	Bridge structure (bi-directional on E_5)
 8	$R_S = R_4 [R_2 + R_1 (R_3 + R_5 - R_3 R_5) - R_1 R_2 (R_3 + R_5 - R_3 R_5)] + (1 - R_4) R_1 R_3$	Bridge structure (unidirectional on E_5)
 9	$R_S = R_2 R_1 (R_4 + R_5 - R_4 R_5) + (1 - R_2) R_1 R_3 R_5$	The element E_2 appears twice in the reliability block diagram (not in the hardware)

(Birolini, 2014)

10.3 Appendix C

Symbol	Name	Significance
	Basic event	This event is an elementary event that does not need explaining.
	Intermediary event	This event is generated by a connection.
	Undeveloped event	This event is not elementary, but it is not developed because it is beyond the scope of the study or because of a lack of information.
	External basic event	The event is supposed to take place during the normal functioning of the system.
	OR gate	The output event takes place if any of the inputs events take place.
	AND gate	The output event takes place if all the input events take place.
	Inhibition gate	The output event takes place when the input event takes place if the condition (represented in the oval) is true.
	Delay gate	The output event takes place with the delay of the duration indicated in relation with the input event.
	**k/n gate** (**k out of** n)	The output event takes place when k of the n inputs take place.
	Input symbol	The upper part of the tree is on the page containing the symbol 101.
	Output symbol	This event is used on another page.

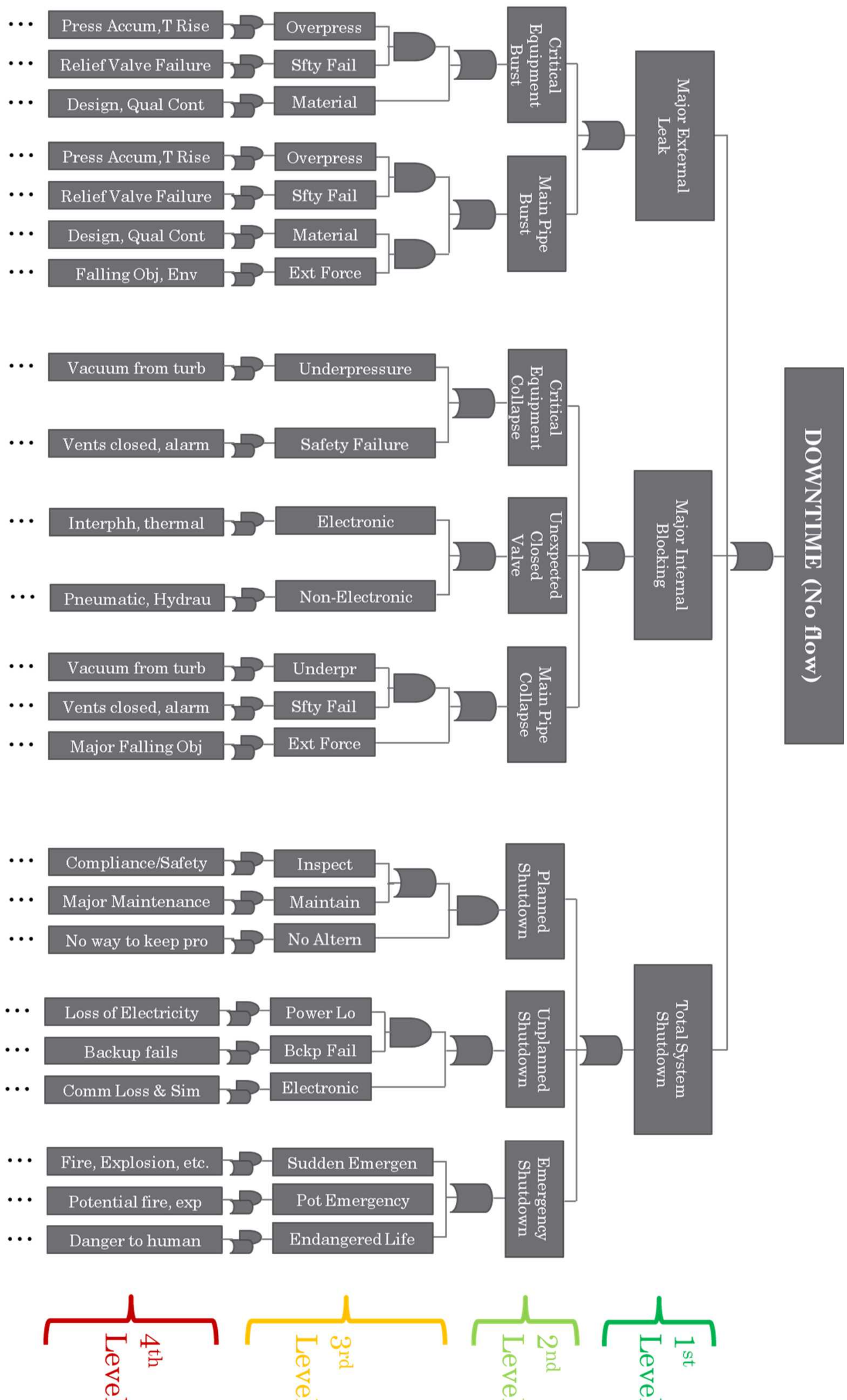
(Flaus, 2013)

10.4 Appendix D

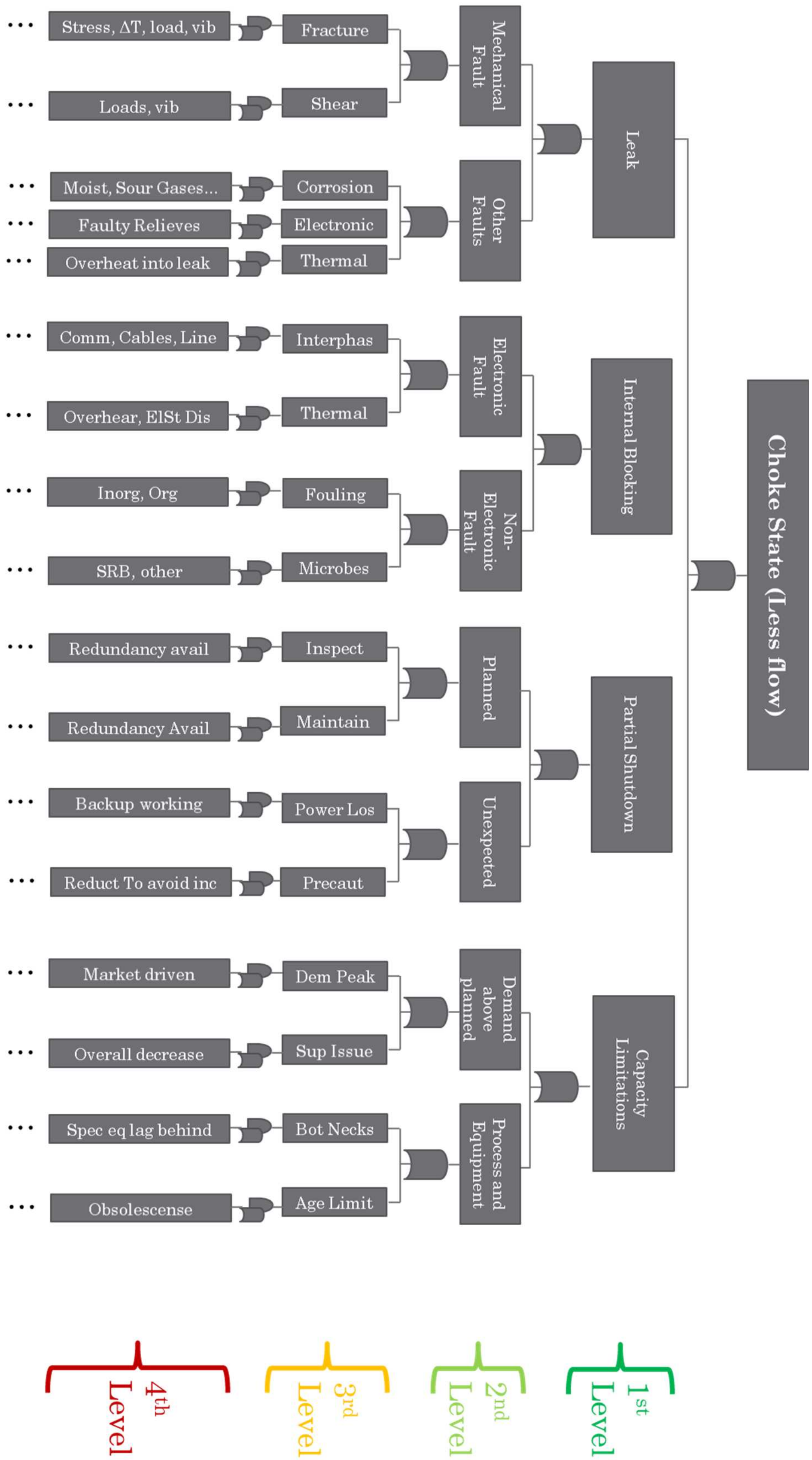
Period	PAYMENT	Payment PV	PRINCIPAL	INTEREST	Interest PV	BALANCE
1	$990.06	$980.26	$698.39	$291.67	$288.78	$49,319.51
2	$990.06	$970.55	$702.47	$287.59	$281.92	$48,634.49
3	$990.06	$960.94	$706.56	$283.49	$275.15	$47,944.90
4	$990.06	$951.43	$710.69	$279.37	$268.47	$47,250.71
5	$990.06	$942.01	$714.83	$275.23	$261.87	$46,551.90
6	$990.06	$932.68	$719.00	$271.06	$255.35	$45,848.43
7	$990.06	$923.45	$723.20	$266.86	$248.91	$45,140.26
8	$990.06	$914.30	$727.41	$262.65	$242.55	$44,427.38
9	$990.06	$905.25	$731.66	$258.40	$236.27	$43,709.74
10	$990.06	$896.29	$735.93	$254.13	$230.06	$42,987.32
11	$990.06	$887.41	$740.22	$249.84	$223.94	$42,260.08
12	$990.06	$878.63	$744.54	$245.52	$217.89	$41,527.99
13	$990.06	$869.93	$748.88	$241.18	$211.92	$40,791.03
14	$990.06	$861.32	$753.25	$236.81	$206.02	$40,049.15
15	$990.06	$852.79	$757.64	$232.42	$200.19	$39,302.32
16	$990.06	$844.34	$762.06	$228.00	$194.44	$38,550.52
17	$990.06	$835.98	$766.51	$223.55	$188.76	$37,793.70
18	$990.06	$827.71	$770.98	$219.08	$183.15	$37,031.84
19	$990.06	$819.51	$775.48	$214.58	$177.62	$36,264.90
20	$990.06	$811.40	$780.00	$210.06	$172.15	$35,492.85
21	$990.06	$803.36	$784.55	$205.51	$166.76	$34,715.65
22	$990.06	$795.41	$789.13	$200.93	$161.43	$33,933.26
23	$990.06	$787.54	$793.73	$196.33	$156.17	$33,145.67
24	$990.06	$779.74	$798.36	$191.70	$150.98	$32,352.82
25	$990.06	$772.02	$803.02	$187.04	$145.85	$31,554.68
26	$990.06	$764.37	$807.70	$182.36	$140.79	$30,751.23
27	$990.06	$756.81	$812.41	$177.65	$135.80	$29,942.42
28	$990.06	$749.31	$817.15	$172.91	$130.86	$29,128.21
29	$990.06	$741.89	$821.92	$168.14	$125.99	$28,308.58
30	$990.06	$734.55	$826.71	$163.35	$121.19	$27,483.49
31	$990.06	$727.28	$831.54	$158.52	$116.45	$26,652.89
32	$990.06	$720.07	$836.39	$153.67	$111.76	$25,816.76
33	$990.06	$712.95	$841.26	$148.79	$107.14	$24,975.05
34	$990.06	$705.89	$846.17	$143.89	$102.59	$24,127.73
35	$990.06	$698.90	$851.11	$138.95	$98.09	$23,274.76
36	$990.06	$691.98	$856.07	$133.99	$93.65	$22,416.11
37	$990.06	$685.13	$861.07	$128.99	$89.26	$21,551.73
38	$990.06	$678.34	$866.09	$123.97	$84.94	$20,681.58
39	$990.06	$671.63	$871.14	$118.92	$80.67	$19,805.64
40	$990.06	$664.98	$876.22	$113.84	$76.46	$18,923.86
41	$990.06	$658.39	$881.33	$108.72	$72.30	$18,036.20
42	$990.06	$651.87	$886.48	$103.58	$68.20	$17,142.62
43	$990.06	$645.42	$891.65	$98.41	$64.15	$16,243.09
44	$990.06	$639.03	$896.85	$93.21	$60.16	$15,337.55
45	$990.06	$632.70	$902.08	$87.98	$56.22	$14,425.98
46	$990.06	$626.44	$907.34	$82.72	$52.34	$13,508.34
47	$990.06	$620.24	$912.64	$77.42	$48.50	$12,584.57
48	$990.06	$614.10	$917.96	$72.10	$44.72	$11,654.65
49	$990.06	$608.01	$923.31	$66.75	$40.99	$10,718.53
50	$990.06	$601.99	$928.70	$61.36	$37.31	$9,776.17
51	$990.06	$596.03	$934.12	$55.94	$33.68	$8,827.52
52	$990.06	$590.13	$939.57	$50.49	$30.09	$7,872.55
53	$990.06	$584.29	$945.05	$45.01	$26.56	$6,911.21
54	$990.06	$578.51	$950.56	$39.50	$23.08	$5,943.47
55	$990.06	$572.78	$956.10	$33.96	$19.65	$4,969.27
56	$990.06	$567.11	$961.68	$28.38	$16.26	$3,988.58
57	$990.06	$561.49	$967.29	$22.77	$12.91	$3,001.35
58	$990.06	$555.93	$972.93	$17.13	$9.62	$2,007.54
59	$990.06	$550.43	$978.61	$11.45	$6.37	$1,007.11
60	$990.06	$544.98	$984.32	$5.74	$3.16	$0.00
		$44,508.19			**$7,688.52**	
		Total Loan PV			Total Interest PV	

Cost of Capital	12.0%
Yealy Interest Rate	7.0%
Year 1 Interest Paid	$3,031.16
Year 2 Interest Paid	$2,169.58
Year 3 Interest Paid	$1,430.17
Year 4 Interest Paid	$797.93
Year 5 Interest Paid	$259.68

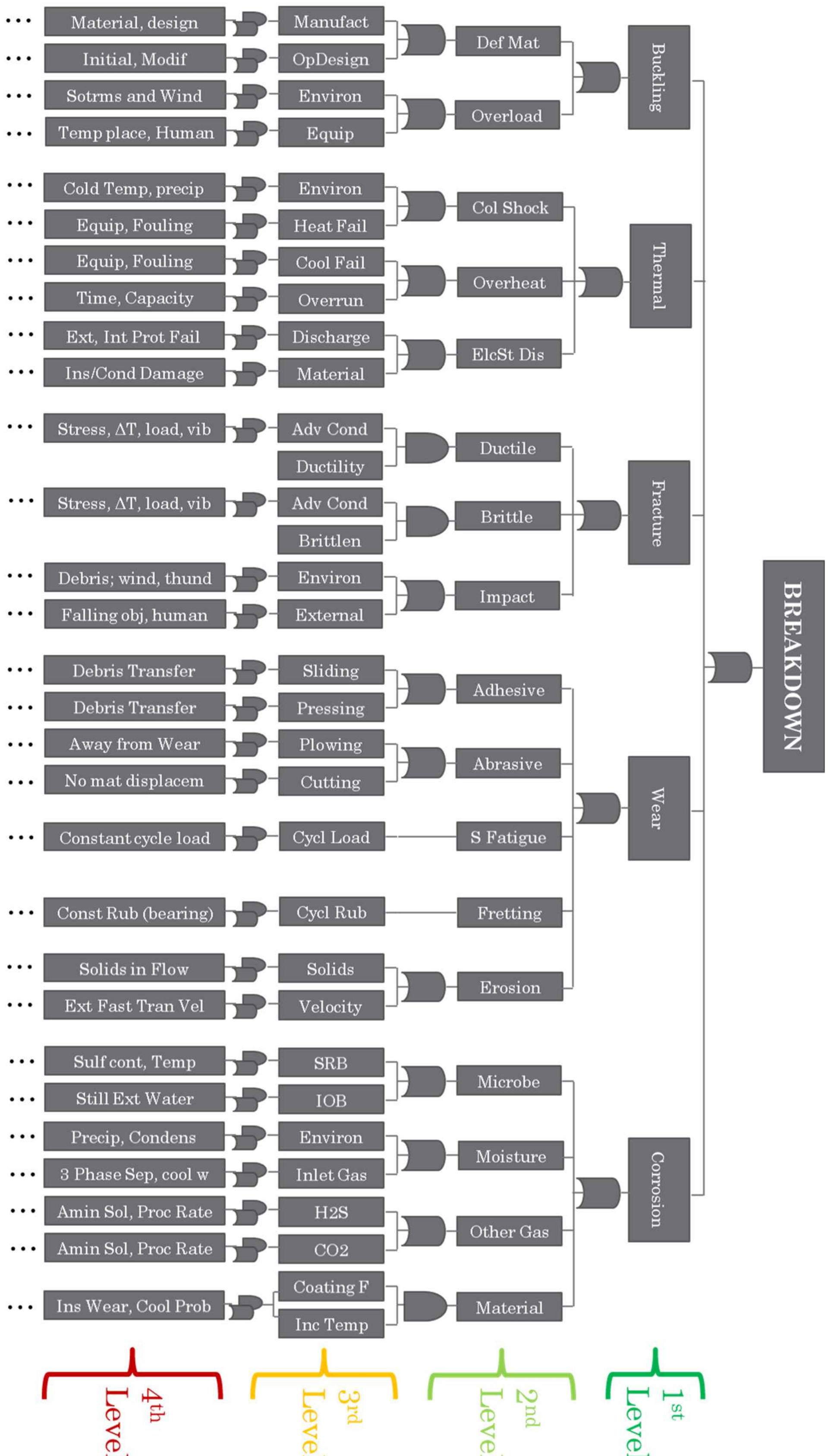
10.5 Appendix E



10.6 Appendix F



10.7 Appendix G

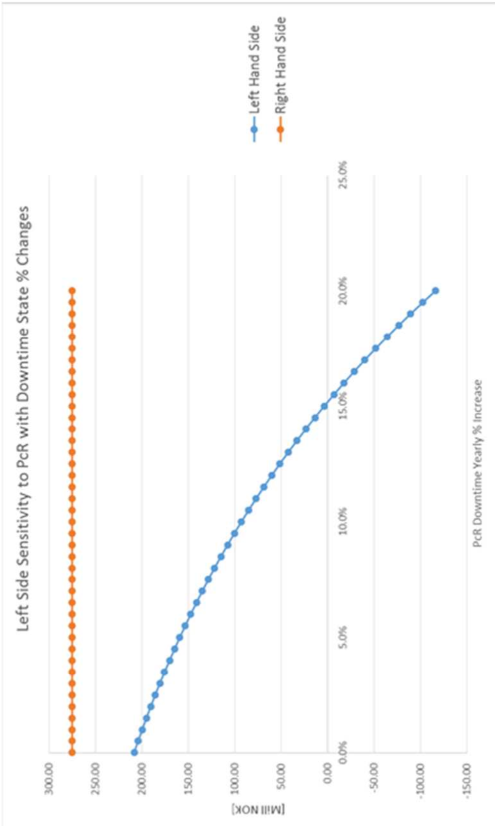


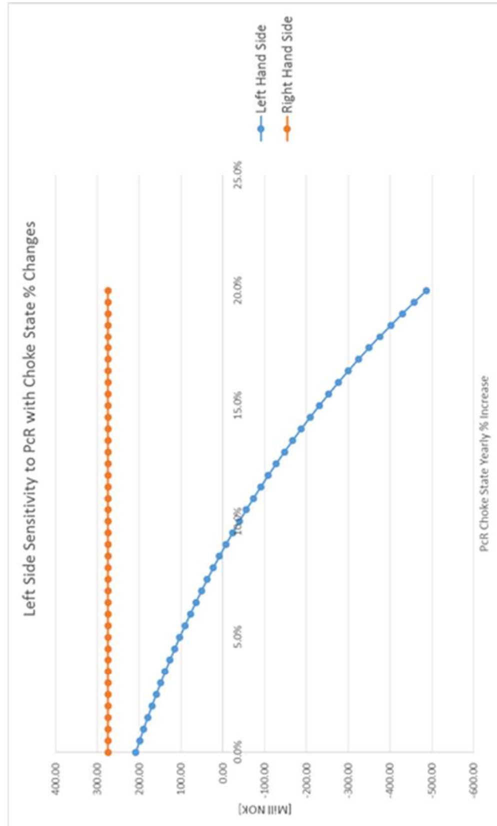
10.8 Appendix H

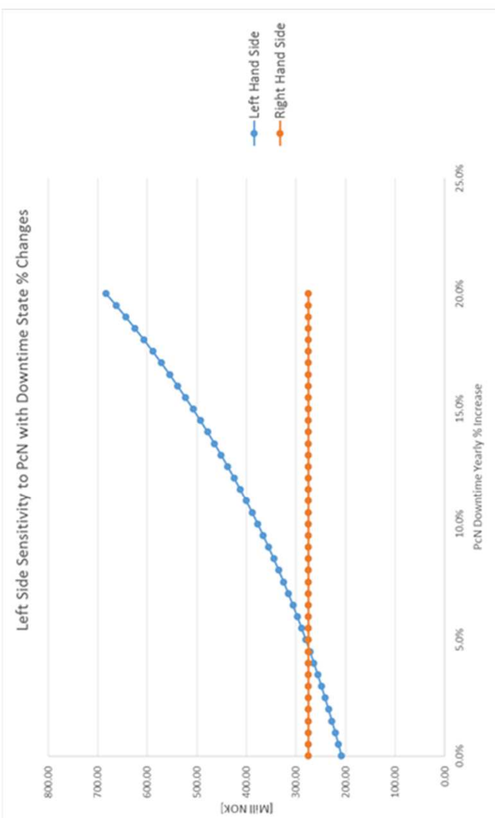
FTA Guideline	Branch	Level	Abbreviation	Full Text
Downtime	First	Third	Overpress	Overpressure
Downtime	First	Third	Sfty Fail	Safety Failure
Downtime	First	Third	Ext Force	External Force
Downtime	First	Fourth	Press Accum	Pressure Accumulation
Downtime	First	Fourth	T Rise	Temperature Rise
Downtime	First	Fourth	Qual Cont	Quality Control
Downtime	First	Fourth	Falling Obj	Falling Object
Downtime	First	Fourth	Env	Environment
Downtime	Second	Third	Underpr	Underpressure
Downtime	Second	Fourth	Vacuum from Turb	Vacuum from Turbine
Downtime	Second	Fourth	Major Falling Obj	Major Falling Object
Downtime	Third	Third	Inspect	Inspection
Downtime	Third	Third	No Altern	No Alternative
Downtime	Third	Third	Power Lo	Power Loss
Downtime	Third	Third	Bckp Fail	Backup Failure
Downtime	Third	Third	Sudden Emergen	Sudden Emergency
Downtime	Third	Third	Pot Emergency	Potential Emergency
Downtime	Third	Fourth	No way to keep Pro	No way to keep Production
Downtime	Third	Fourth	Exp	Explosion
Downtime	Third	Fourth	Com Loss	Communication Loss
Downtime	Third	Fourth	Sim	Simulation
Choke State	First	Fourth	Vib	Vibration
Choke State	Second	Third	Interphas	Interphase
Choke State	Second	Fourth	Elst Dis	Electrostatic Discharge
Choke State	Second	Fourth	Inorg	Inorganic
Choke State	Second	Fourth	Org	Organic
Choke State	Second	Fourth	SRB	Sulfate Reducing Bacteria
Choke State	Third	Third	Precaut	Precautionary
Choke State	Third	Fourth	Redundancy Avail	Redundancy Available
Choke State	Third	Fourth	Reduct to avoid Inc	Reduction to avoid Increased Risk
Choke State	Fourth	Third	Dem Peak	Demand Peak
Choke State	Fourth	Third	Sup Issue	Supply Issue
Choke State	Fourth	Third	Bot Necks	Bottlenecks
Choke State	Fourth	Fourth	Spec eq lag behind	Specific equipment lagging behind
Breakdown	First	Second	Def Material	Deficient Material
Breakdown	First	Third	Manufact	Manufacturing
Breakdown	First	Third	OpDesign	Operational Design
Breakdown	First	Third	Environ	Environment
Breakdown	First	Third	Equip	Equipment
Breakdown	First	Fourth	Modif	Modifications

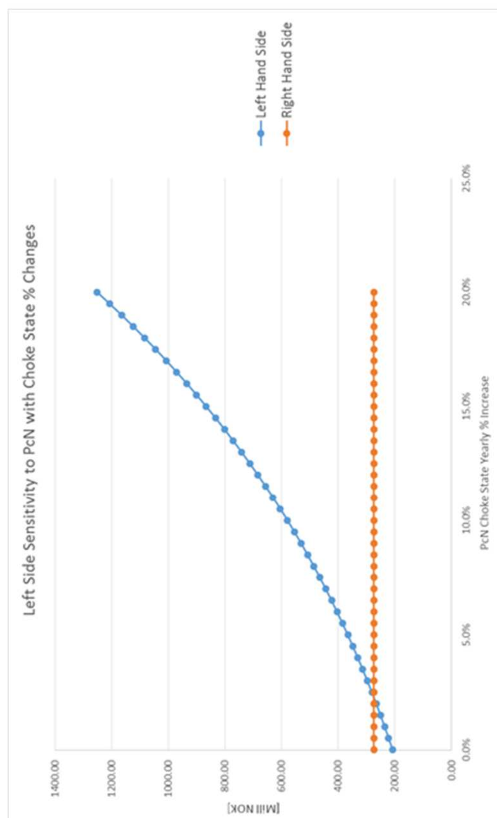
Breakdown	First	Fourth	Temp	Temperature
Breakdown	Second	Second	Col Shock	Cold Shock
Breakdown	Second	Third	Heat Fail	Heat Failure
Breakdown	Second	Third	Cool Fail	Cooling Failure
Breakdown	Second	Fourth	Precip	Precipitation
Breakdown	Second	Fourth	Ext	External Force
Breakdown	Second	Fourth	Int Prot Fail	Internal Protection Failure
Breakdown	Second	Fourth	Ins/Cond Damage	Insulation/Condition Damage
Breakdown	Third	Third	Adv Condition	Adverse Condition
Breakdown	Third	Fourth	Thund	Thunder
Breakdown	Fourth	Third	Cyc Load	Cyclic Load
Breakdown	Fourth	Third	Cyc Rub	Cyclic Rubbing
Breakdown	Fourth	Fourth	No Mat Displacem	No Material Displacement
Breakdown	Fourth	Fourth	Cont Rub	Constant Rubbing
Breakdown	Fourth	Fourth	Ext Fast Tran Vel	Extremely Fast Transversal Velocity
Breakdown	Fifth	Third	IOB	Iron Oxidizing Bacteria
Breakdown	Fifth	Third	Coating F	Coating Failure
Breakdown	Fifth	Third	Inc Temp	Increasing Temperature
Breakdown	Fifth	Fourth	Sulf Cont	Sulfur Content
Breakdown	Fifth	Fourth	Still Ext Water	Still External Water
Breakdown	Fifth	Fourth	Condens	Condensation
Breakdown	Fifth	Fourth	3-Phase Sep	3-Phase Separator
Breakdown	Fifth	Fourth	Cool w	Cooling Water
Breakdown	Fifth	Fourth	Proc Rate	Procreation Rate
Breakdown	Fifth	Fourth	Ins Wear	Insulation Wear
Breakdown	Fifth	Fourth	Cool Prob	Cooling Problems

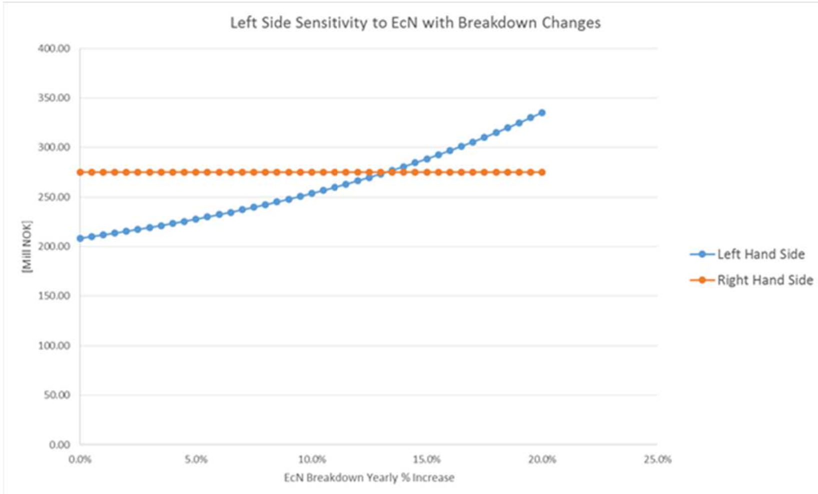
10.9 Appendix I

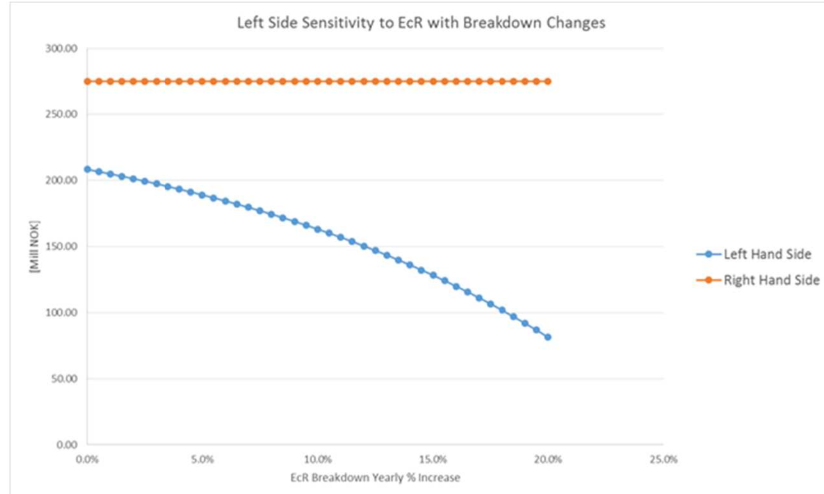


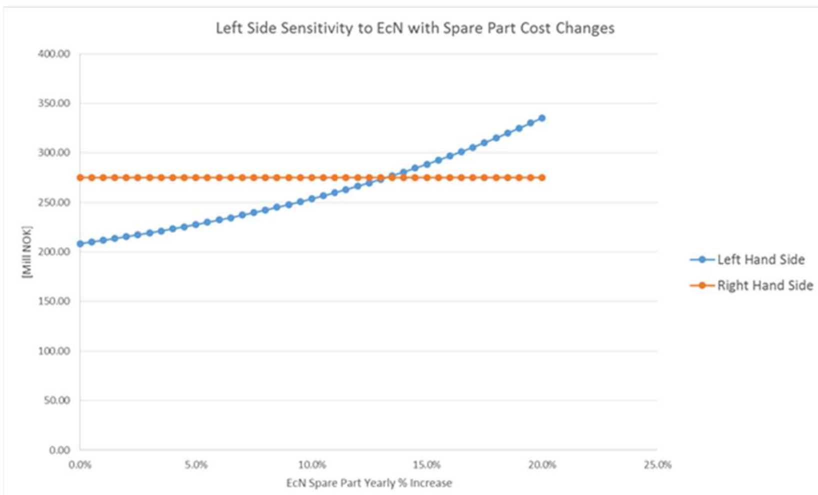


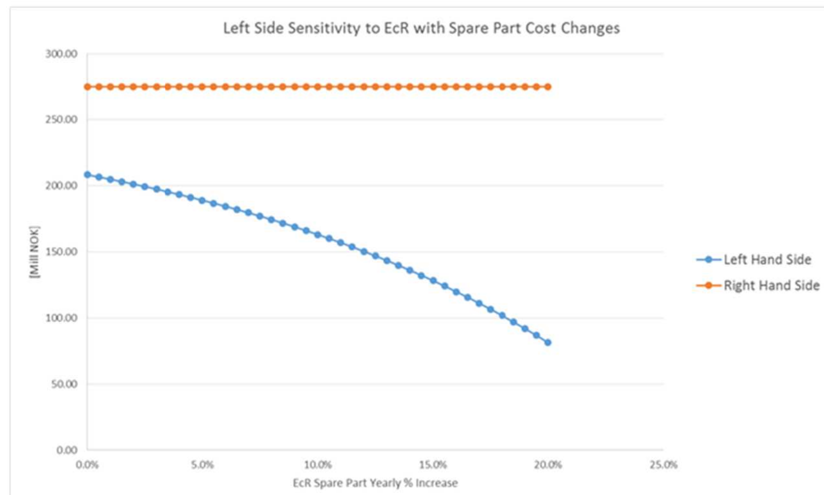


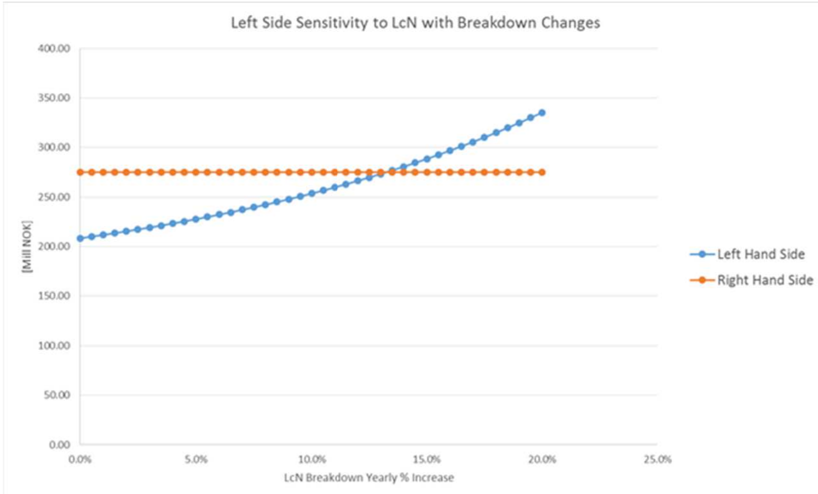


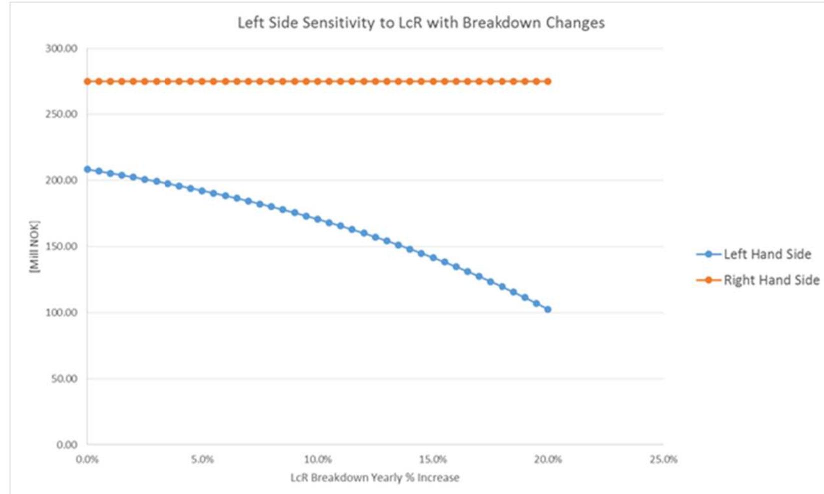

Left Side Sensitivity to EcN with Breakdown Changes
[Mill NOK]
400.00
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
0.0%
5.0%
10.0%
15.0%
20.0%
25.0%
EcN Breakdown Yearly % Increase
Left Hand Side
Right Hand Side

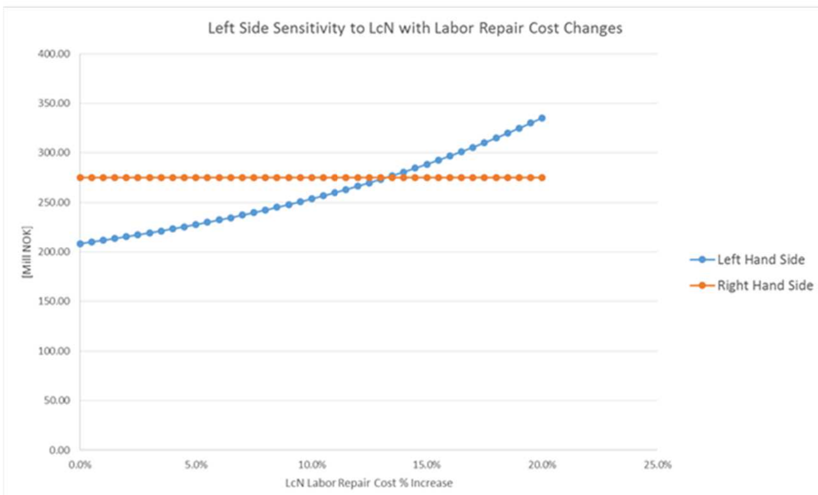

Left Side Sensitivity to EcR with Breakdown Changes
[Mill NOK]
300.00
250.00
200.00
150.00
100.00
50.00
0.00
0.0%
5.0%
10.0%
15.0%
20.0%
25.0%
EcR Breakdown Yearly % Increase
Left Hand Side
Right Hand Side

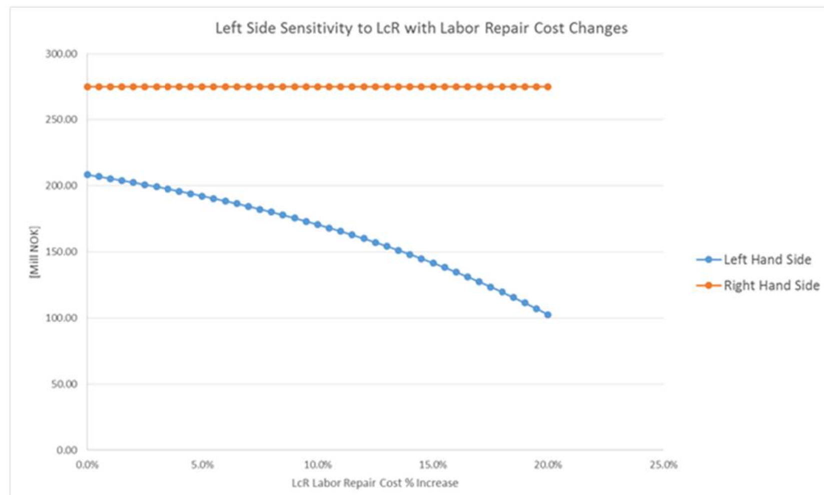

Left Side Sensitivity to EcN with Spare Part Cost Changes
[Mill NOK]
400.00
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
0.0%
5.0%
10.0%
15.0%
20.0%
25.0%
EcN Spare Part Yearly % Increase
Left Hand Side
Right Hand Side

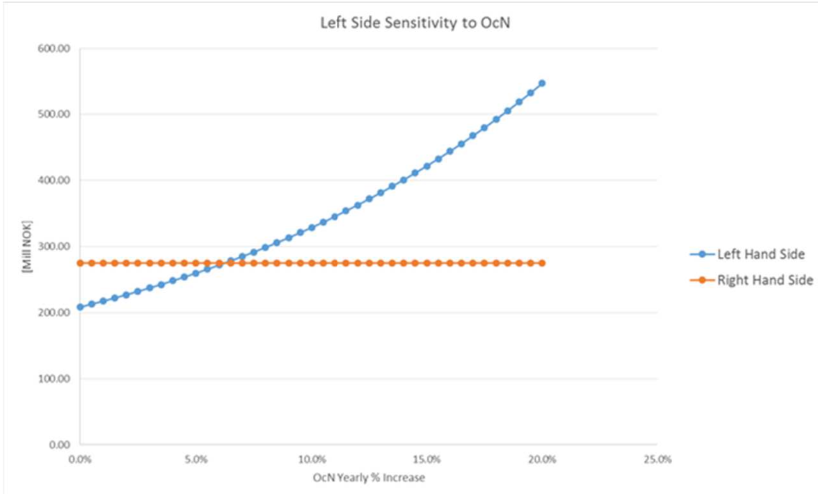

Left Side Sensitivity to EcR with Spare Part Cost Changes
[Mill NOK]
300.00
250.00
200.00
150.00
100.00
50.00
0.00
0.0%
5.0%
10.0%
15.0%
20.0%
25.0%
EcR Spare Part Yearly % Increase
Left Hand Side
Right Hand Side

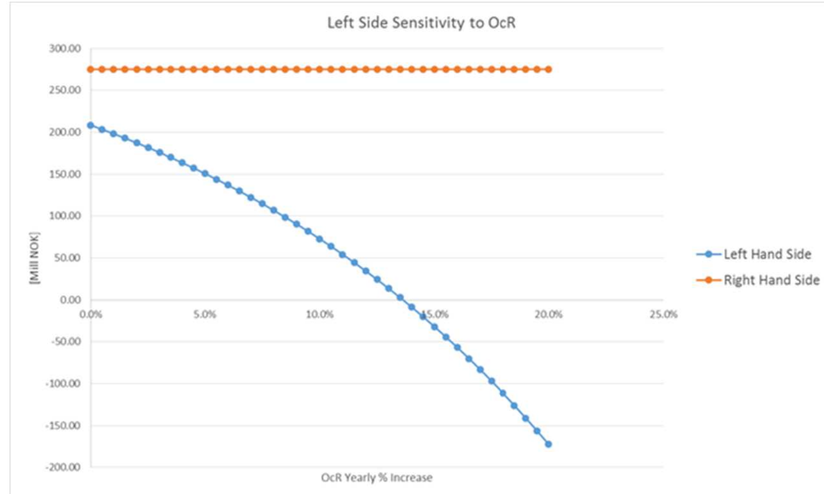

Left Side Sensitivity to LcN with Breakdown Changes
[Mill NOK]
LcN Breakdown Yearly % Increase
Left Hand Side
Right Hand Side

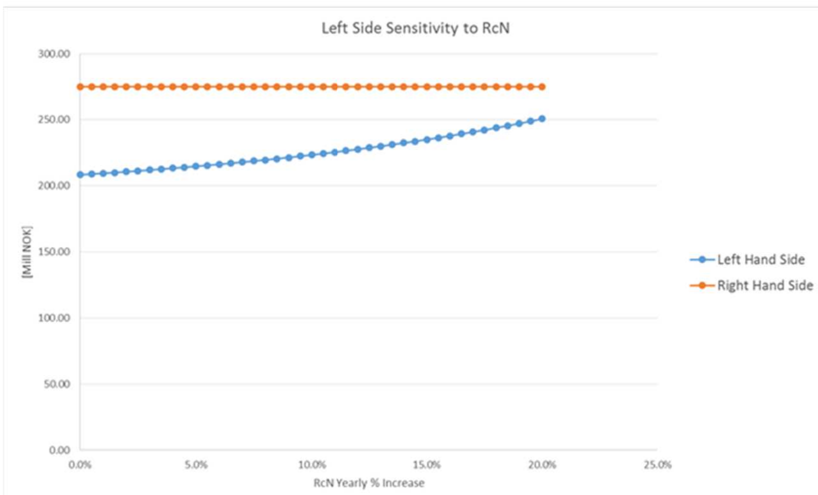

Left Side Sensitivity to LcR with Breakdown Changes
[Mill NOK]
LcR Breakdown Yearly % Increase
Left Hand Side
Right Hand Side

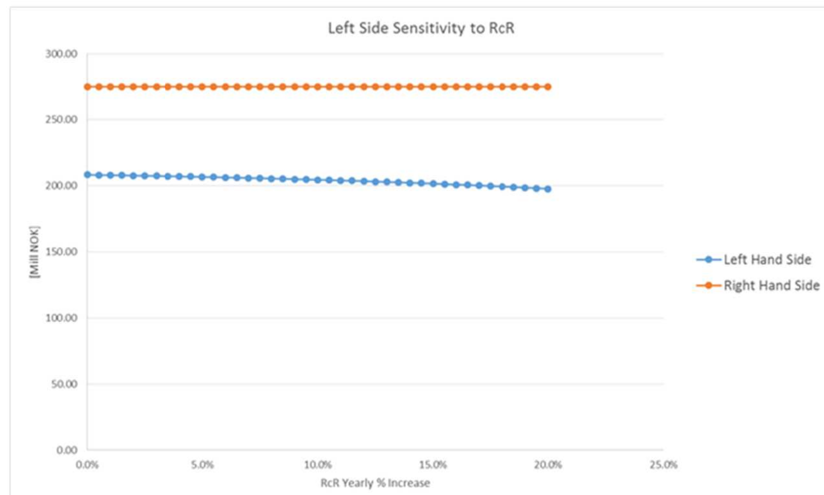

Left Side Sensitivity to LcN with Labor Repair Cost Changes
[Mill NOK]
LcN Labor Repair Cost % Increase
Left Hand Side
Right Hand Side

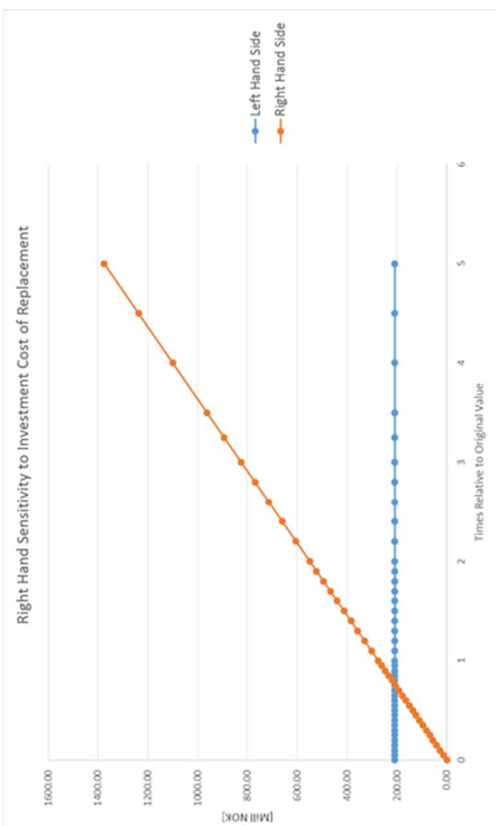

Left Side Sensitivity to LcR with Labor Repair Cost Changes
[Mill NOK]
LcR Labor Repair Cost % Increase
Left Hand Side
Right Hand Side

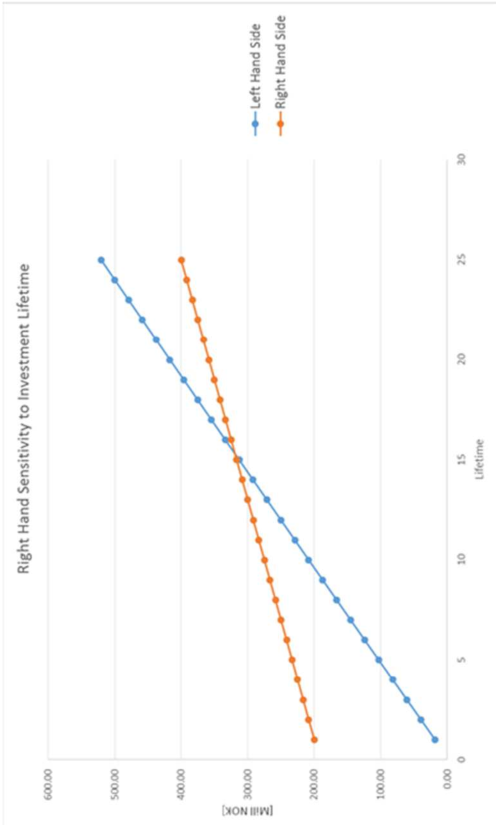

Left Side Sensitivity to OcN
[Mill NOK]
600.00
500.00
400.00
300.00
200.00
100.00
0.00
0.0%
5.0%
10.0%
15.0%
20.0%
25.0%
OcN Yearly % Increase
Left Hand Side
Right Hand Side

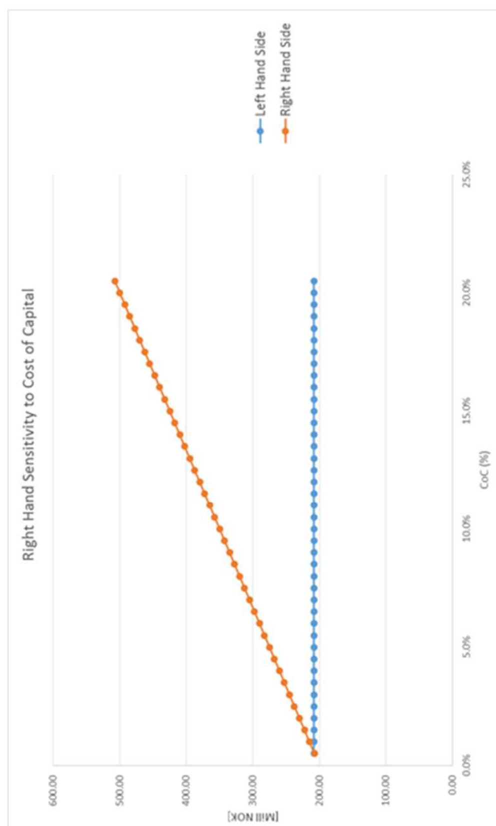

Left Side Sensitivity to OcR
[Mill NOK]
300.00
250.00
200.00
150.00
100.00
50.00
0.00
-50.00
-100.00
-150.00
-200.00
0.0%
5.0%
10.0%
15.0%
20.0%
25.0%
OcR Yearly % Increase
Left Hand Side
Right Hand Side

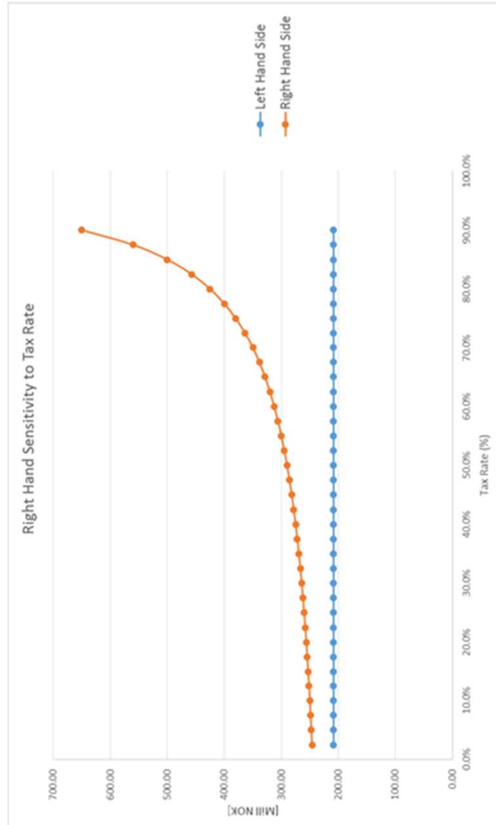

Left Side Sensitivity to RcN
[Mill NOK]
300.00
250.00
200.00
150.00
100.00
50.00
0.00
0.0%
5.0%
10.0%
15.0%
20.0%
25.0%
RcN Yearly % Increase
Left Hand Side
Right Hand Side


Left Side Sensitivity to RcR
[Mill NOK]
300.00
250.00
200.00
150.00
100.00
50.00
0.00
0.0%
5.0%
10.0%
15.0%
20.0%
25.0%
RcR Yearly % Increase
Left Hand Side
Right Hand Side


Right Hand Sensitivity to Investment Cost of Replacement
[Mill NOK]
Times Relative to Original Value
Left Hand Side
Right Hand Side


Right Hand Sensitivity to Investment Lifetime
[Mill NOK]
Lifetime
Left Hand Side
Right Hand Side


Right Hand Sensitivity to Cost of Capital
[Mill NOK]
CoC (%)
Left Hand Side
Right Hand Side


Right Hand Sensitivity to Tax Rate
[Mill NOK]
Tax Rate (%)
Left Hand Side
Right Hand Side

10.10 Appendix J

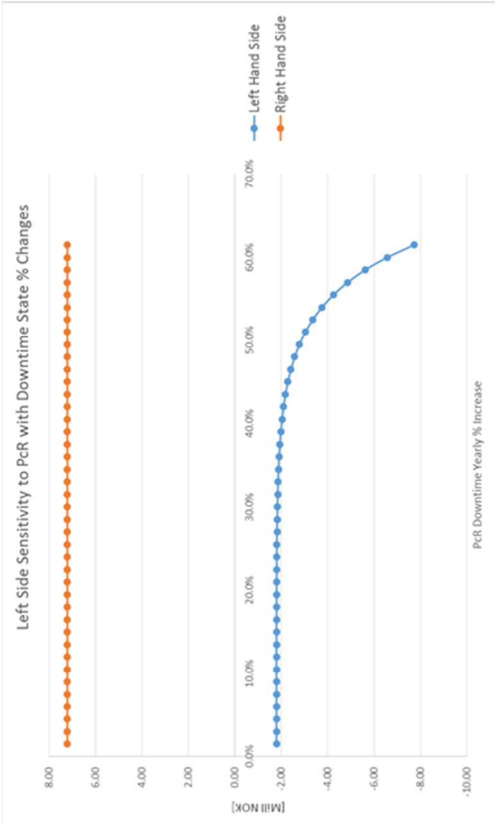
Substation	UPS	Section	Priority	Failure Im	Breakdown	Tot Act ho	Notif Crea	Basic Star	TECO Date	TECO - Start	Max Repair Time	Time til Fail	No. of act	Op Text	Work	Act Work
A52B	α	Battery Bank	L			22.0	10/15/1999	10/18/1999	11/22/1999	35	38	First	3	Rengjør og	60	22000
A52B	α	Battery Bank	L			0.0	11/19/2003	12/30/2003	12/23/2003	-7	34	1492.00	0	Skifte batt	0	0
A52B	α	Battery Bank	L			135.0	1/6/2004	1/11/2004	2/26/2004	46	51	65.00	1	Skifte batt	25	135000
A52B	α	Battery Bank	U			6.0	1/15/2004	2/1/2004	2/5/2004	4	21	21.00	1	Kontroll av	8	6000
A52B	α	Battery Bank	L			5.0	2/5/2004	5/3/2004	6/23/2004	51	139	139.00	1	4.mnd. kor	11	5000
A52B	α	Battery Bank	L			111.0	9/27/2004	10/17/2004	9/7/2006	690	710	806.00	1	Skifte defe	20	111000
A52B	α	Battery Bank	M	S		12.5	9/30/2011	10/17/2011	10/26/2011	9	26	1875.00	1	Planlegging	18	12500
A52B	α	Battery Bank	H	D	X	44.5	1/19/2012	1/19/2012	1/30/2012	11	11	96.00	4	Feilsøkjing	37	44500
A52B	α	Battery Bank	L	S		7.5	5/9/2012	10/15/2012	10/19/2012	4	163	263.00	1	Planlegge/	10	7500
A52B	α	Battery Bank	L	S		9.0	5/12/2014	1/21/2015	2/11/2015	21	275	845.00	1	Kjøre ned	11	9000
A52B	α	Battery Bank	U	U		0.0	6/8/2015	7/8/2015	7/10/2015	2	32	149.00	1	Lav spenni	0	0
A52B	α	Distribution Board	L			3.0	1/28/2005	2/12/2005	3/4/2005	20	35	First	1	A14, UPS, I	7.5	3000
A52B	α	UPS	M			2.0	1/3/2001	1/8/2001	1/18/2001	10	15	First	1	Skifte kon	8	2000
A52B	α	UPS	L			91.0	12/13/2001	1/23/2002	1/22/2002	-1	40	369.00	0	Skifte kon	70	91000
A52B	α	UPS	H	S		4.0	1/19/2012	1/19/2012	1/20/2012	1	1	3650.00	0	Feilsøking	4	4000
A52B	β	Battery Bank	U			11.0	1/29/2001	10/12/2001	10/18/2001	6	262	First	0	Skifte batt	8	11000
A52B	β	Battery Bank	L			0.0	11/28/2003	12/30/2003	12/17/2003	-13	19	790.00	0			
A52B	β	Battery Bank	U			63.0	9/23/2004	10/13/2004	1/21/2005	100	120	401.00	1	Skifte batt	30	63000
A52B	β	Battery Bank	U	U		0.0	11/26/2007	6/29/2009	7/6/2009	7	588	1627.00	1	Fjerne bat.	6	0
A52B	β	Battery Bank	L	S		415.5	2/15/2008	11/23/2009	6/10/2010	199	846	339.00	1			
A52B	β	Battery Bank	L	S		10.0	11/23/2011	2/20/2012	2/29/2012	9	98	629.00	1	Planlegge/	8	10000
A52B	β	Battery Bank	L	S		7.0	5/8/2012	10/15/2012	10/19/2012	4	164	233.00	1	Planlegge/	10	7000
A52B	β	Battery Bank	L	U		11.5	6/26/2015	12/22/2015	1/7/2016	16	195	1175.00	1	Kjøre ned	12	11500
A52B	β	UPS	L			91.0	12/13/2001	1/23/2002	1/22/2002	-1	40	First	0			
A52B	β	UPS	H	D	X	7.0	2/7/2015	2/7/2015	2/9/2015	2	2	4766.00	1	***VAKTU	8	7000
A53B	α	Battery Bank	U			8.0	1/29/2001	10/12/2001	10/18/2001	6	262	First	0	Skifte batt	8	8000
A53B	α	Battery Bank	U			19.0	9/23/2004	10/13/2004	1/21/2005	100	120	1191.00	1	Skifte batt	25	19000
A53B	α	Battery Bank	L			70.5	3/7/2005	3/22/2005	1/17/2006	301	316	361.00	1	A53B, Batt	66	70500
A53B	α	Battery Bank	U	U		415.5	11/10/2006	11/23/2009	6/10/2010	199	1308	1605.00	1	Timer ass.	554	415500
A53B	α	Battery Bank	U	U		22.0	7/8/2011	3/28/2014	3/31/2014	3	997	1390.00	1	verifisere l	19	22000
A53B	α	Battery Bank	M	S		13.0	4/9/2014	5/20/2014	5/20/2014	0	41	50.00	1	Kjøre ned	12	13000
A53B	α	UPS	M			1.0	1/3/2001	1/3/2001	1/18/2001	15	15	First	1	Skifte kon	8	1000
A53B	α	UPS	L			91.0	12/13/2001	1/23/2002	1/22/2002	-1	40	369.00	0			
A53B	α	UPS	L			0.0	9/19/2003	10/4/2003	3/17/2004	165	180	785.00	1			
A53B	α	UPS	M			6.0	8/20/2005	8/27/2005	10/28/2005	62	69	590.00	1	Vaktutkall	3	6000
A53B	α	UPS	U			3.0	8/2/2006	8/22/2006	8/2/2006	-20	0	278.00	1	Vaktutkall	0	3000
A53B	α	UPS	H	S		27.0	8/2/2008	8/2/2008	12/8/2008	128	128	859.00	3	Vaktutkall.	43	27000
A53B	α	UPS	L	D	X	18.0	1/7/2010	3/8/2010	3/12/2010	4	64	459.00	1	Feilsøking	30	18000
A53B	α	UPS	U	U		11.5	3/12/2010	9/19/2011	9/20/2011	1	557	557.00	1	Kontroll av	20	11500
A53B	α	UPS	U	S		39.0	10/10/2013	4/8/2014	9/21/2014	166	346	1097.00	1	Tune kort/	12	39000
A53B	β	Battery Bank	M			0.0	11/28/2003	12/30/2003	12/17/2003	-13	19	First	0			
A53B	β	Battery Bank	U			7.5	9/23/2004	10/13/2004	1/21/2005	100	120	401.00	1	Skifte batt	25	7500
A53B	β	Battery Bank	U	U		14.0	6/29/2010	4/2/2011	4/13/2011	11	288	2273.00	2	Korrosjon	14	14000
A53B	β	Battery Bank	U	U		43.5	7/8/2011	3/28/2014	3/31/2014	3	997	1083.00	2	verifisere l	18	43500
A53B	β	Battery Bank	M	S		68.5	4/9/2014	6/2/2015	8/6/2015	65	484	493.00	1	Kjøre ned	80	68500
A53B	β	UPS	L			0.0	9/7/2001	11/29/2001	12/13/2002	379	462	First	1	Støy av UF	15	0
A53B	β	UPS	L			103.5	11/7/2001	8/31/2003	9/11/2003	11	673	272.00	0	Skifte tran	101	103500
A53B	β	UPS	L			91.0	12/13/2001	1/23/2002	1/22/2002	-1	40	597.00	0			
A53B	β	UPS	H			40.0	9/11/2006	9/11/2006	9/12/2006	1	1	1694.00	1	5 stk. 1. Pr	0	40000
A53B	β	UPS	H	D	X	5.5	2/23/2010	2/23/2010	2/25/2010	2	2	1262.00	1	Frekvensfe	0	5500
A53B	β	UPS	L	S		2.5	3/11/2010	4/21/2010	4/21/2010	0	41	55.00	1	Bytte A105	20	2500
A53B	β	UPS	H	S		25.0	9/18/2013	10/18/2013	9/19/2013	-29	1	1247.00	1	Feilsøking	27	25000
A53B	β	UPS	U	U		0.0	11/29/2013	12/29/2013	3/14/2014	75	105	176.00	1	UPS 2. pric	0	0
A53B	β	UPS	L	D	X	7.0	3/30/2014	4/7/2014	4/9/2014	2	10	26.00	1	Feilsøke U	10	7000

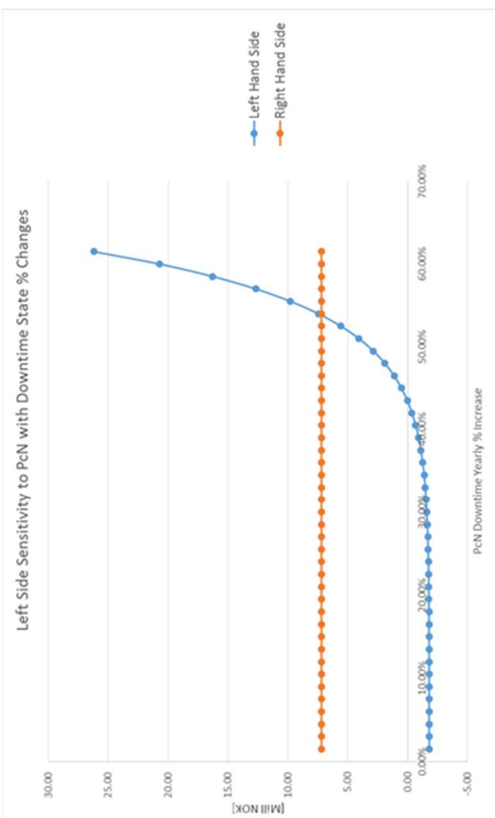
10.11 Appendix K

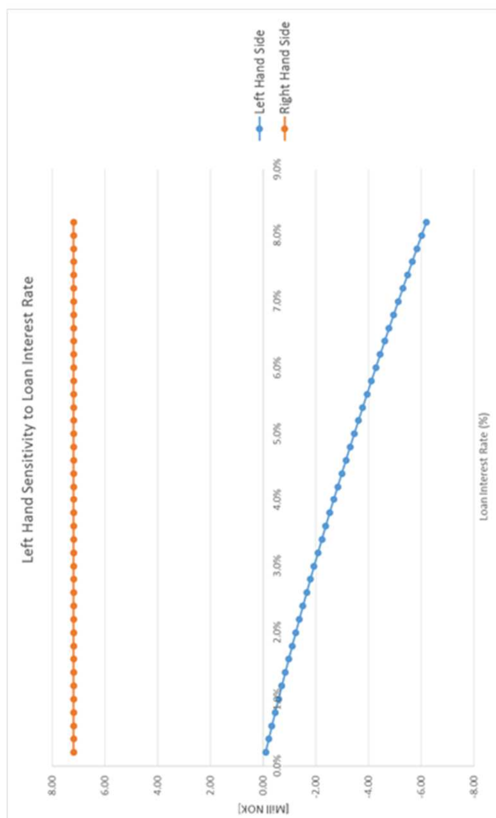
SubStation	Description	Component	Breakdown?	Start Date	Repair Cost
A52B	Etterfylling av	Battery	N	10/18/1999	4,941.94
A52B	48M FV_EL 23	Inverter	N	1/1/2000	8,084.50
A52B	48M FV_EL 23	Inverter	N	1/1/2000	4,807.00
A52B	Skifte konden	Rectifier	N	1/8/2001	876.00
A52B	x12mFV_EL 2.	Inverter	N	1/29/2001	1,314.00
A52B	12M FV_EL 23	Inverter	N	2/19/2001	1,314.00
A52B	12M FV_EL 23	Inverter	N	3/6/2002	7,436.08
A52B	12M FV_EL 23	Inverter	N	3/7/2002	4,650.61
A52B	12M FV_EL 23	Inverter	N	1/1/2003	3,435.00
A52B	12M FV_EL 23	Inverter	N	1/1/2003	9,847.00
A52B	Skifte batterib	Battery	N	12/30/2003	155,718.00
A52B	Skifte batterib	Battery	N	1/11/2004	52,147.52
A52B	Kontroll av ny	Battery	N	2/1/2004	2,910.00
A52B	48M FV_EL 23	Inverter	N	2/23/2004	5,627.56
A52B	48M FV_EL 23	Inverter	N	2/24/2004	1,194.04
A52B	4.mnd. kontro	Battery	N	5/3/2004	2,294.52
A52B	Skifte defekte	Battery	N	10/17/2004	56,488.23
A52B	12M FV_EL 23	Inverter	N	1/1/2005	1,188.03
A52B	12M FV_EL 23	Inverter	N	1/1/2005	1,782.05
A52B	A14, UPS, leka	Battery	N	2/12/2005	1,524.00
A52B	12M FV_EL 23	Inverter	N	1/1/2006	11,872.14
A52B	12M FV_EL 23	Inverter	N	1/1/2006	7,994.05
A52B	12M FV_EL 23	Inverter	N	1/1/2007	3,415.50
A52B	12M FV_EL 23	Inverter	N	1/1/2007	4,657.50
A52B	48M FV_EL 23	Inverter	N	1/21/2008	5,591.00
A52B	48M FV_EL 23	Inverter	N	1/22/2008	7,467.00
A52B	12M FV_EL 23	Inverter	N	1/1/2009	2,492.00
A52B	12M FV_EL 23	Inverter	N	1/1/2009	1,869.00
A52B	12M FV_EL 23	Inverter	N	1/11/2010	5,661.00
A52B	12M FV_EL 23	Inverter	N	1/11/2010	0.00
A52B	48M FV_EL 23	Inverter	N	2/22/2010	4,152.50
A52B	48M FV_EL 23	Inverter	N	2/22/2010	4,530.00
A52B	12M FV_EL 23	Inverter	N	4/4/2011	6,772.50
A52B	12M FV_EL 23	Inverter	N	4/4/2011	3,870.00
A52B	Bytte batterie	Battery	N	10/17/2011	17,094.90
A52B	Vakt utkall UP	Battery	Y	1/19/2012	2,928.00
A52B	Alarm på UPS	Battery	Y	1/19/2012	29,878.00
A52B	24M FV_EL 23	Inverter	N	4/30/2012	5,856.00
A52B	24M FV_EL 23	Inverter	N	4/30/2012	5,490.00
A52B	Bytte batteri	Battery	N	10/15/2012	17,611.31
A52B	12M FV_EL 23	Inverter	N	5/13/2013	6,391.50
A52B	12M FV_EL 23	Inverter	N	5/23/2013	10,597.50
A52B	24M FV_EL 23	Inverter	N	5/15/2014	17,662.50
A52B	24M FV_EL 23	Inverter	N	5/22/2014	18,447.50
A52B	Lav spenning	Battery	N	1/21/2015	6,831.00
A52B	***VAKTUTK/	Reactive	Y	2/7/2015	5,238.00
A52B	12M FV_EL 23	Inverter	N	6/15/2015	10,260.00
A52B	12M FV_EL 23	Inverter	N	6/22/2015	13,236.00
A52B	Lav spenning	Battery	N	7/8/2015	0.00
A52B	24M FV_EL 23	Inverter	N	6/13/2016	0.00
A52B	24M FV_EL 23	Inverter	N	6/16/2016	0.00
A53B	48M FV_EL 23	Inverter	N	2/28/2000	24,824.00
A53B	48M FV_EL 23	Inverter	N	2/28/2000	33,942.50
A53B	Skifte konden	Rectifier	N	1/3/2001	438.00
A53B	x12MFV_EL 2	Inverter	N	1/29/2001	1,533.00

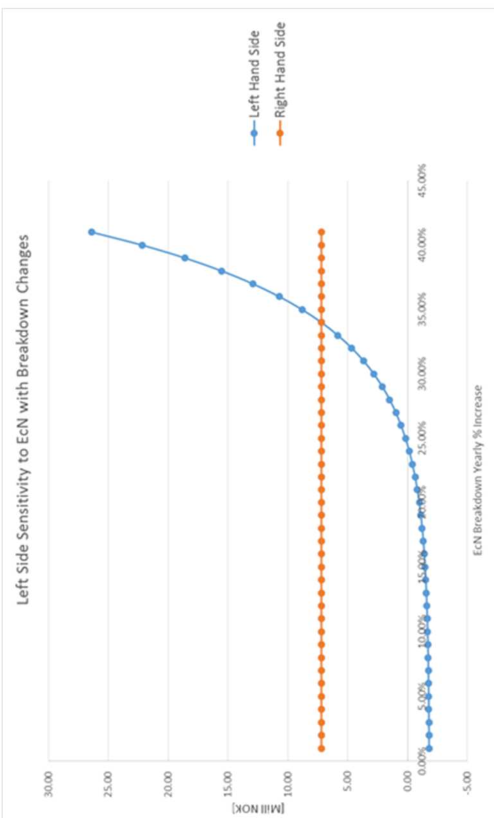
SubStation	Description	Component	Breakdown?	Start Date	Repair Cost
A53B	12M FV_EL 2	Inverter	N	2/19/2001	1,314.00
A53B	Skifte batteri	Battery	N	10/12/2001	3,625.04
A53B	Støy av UPS	Reactive	N	11/29/2001	27,700.00
A53B	12M FV_EL 2	Inverter	N	2/28/2002	5,361.58
A53B	12M FV_EL 2	Inverter	N	2/28/2002	7,058.10
A53B	12M FV_EL 2	Inverter	N	1/1/2003	2,977.00
A53B	12M FV_EL 2	Inverter	N	1/1/2003	10,992.00
A53B	Skifte tranfor	Rectifier	N	8/31/2003	85,243.40
A53B	48M FV_EL 2	Inverter	N	2/25/2004	4,126.02
A53B	48M FV_EL 2	Inverter	N	2/25/2004	6,293.02
A53B	Skifte batteri	Battery	N	10/13/2004	169,013.00
A53B	Skifte batteri	Battery	N	10/13/2004	165,079.50
A53B	12M FV_EL 2	Inverter	N	1/1/2005	792.02
A53B	12M FV_EL 2	Inverter	N	1/1/2005	792.02
A53B	A53B, Batteri	Battery	N	3/22/2005	31,366.53
A53B	Feil på UPS i	Reactive	N	8/27/2005	3,048.00
A53B	12M FV_EL 2	Inverter	N	1/1/2006	4,600.12
A53B	12M FV_EL 2	Inverter	N	1/1/2006	0.00
A53B	Vaktutkall UF	Reactive	N	8/22/2006	1,911.00
A53B	5 stk. 1. Prior	Reactive	N	9/11/2006	20,920.16
A53B	12M FV_EL 2	Inverter	N	1/1/2007	2,484.00
A53B	12M FV_EL 2	Inverter	N	1/1/2007	5,899.50
A53B	48M FV_EL 2	Inverter	N	1/21/2008	2,948.00
A53B	48M FV_EL 2	Inverter	N	1/22/2008	2,680.00
A53B	#Bytte og tur	Reactive	N	8/2/2008	37,172.00
A53B	12M FV_EL 2	Inverter	N	1/1/2009	3,918.00
A53B	12M FV_EL 2	Inverter	N	1/1/2009	2,180.50
A53B	12M FV_EL 2	Inverter	N	1/18/2010	0.00
A53B	12M FV_EL 2	Inverter	N	1/18/2010	0.00
A53B	Feilsøking på	Reactive	Y	2/23/2010	4,152.50
A53B	48M FV_EL 2	Inverter	Y	3/3/2010	6,417.50
A53B	Feilsøking på	Reactive	Y	3/8/2010	73,568.74
A53B	48M FV_EL 2	Inverter	Y	3/8/2010	4,907.50
A53B	Bytte powers	Reactive	N	4/21/2010	28,339.13
A53B	Utbedre korr	Battery	N	4/2/2011	9,460.00
A53B	12M FV_EL 2	Inverter	N	4/4/2011	4,837.50
A53B	12M FV_EL 2	Inverter	N	4/4/2011	2,580.00
A53B	Kontroll av st	Rectifier	N	9/19/2011	7,027.50
A53B	24M FV_EL 2	Inverter	N	4/30/2012	5,856.00
A53B	24M FV_EL 2	Inverter	N	4/30/2012	5,490.00
A53B	12M FV_EL 2	Inverter	N	5/14/2013	7,457.50
A53B	12M FV_EL 2	Inverter	N	5/22/2013	9,027.50
A53B	UPS, LR AC SI	Reactive	N	10/18/2013	21,389.00
A53B	UPS 2. priorit	Reactive	N	12/29/2013	0.00
A53B	Bytte batteri	Battery	N	3/28/2014	77,930.00
A53B	Lekkasje batt	Battery	N	3/28/2014	17,275.25
A53B	UPS, Likerett	Reactive	Y	4/7/2014	5,495.00
A53B	#2. prioritet	Reactive	Y	4/8/2014	85,849.30
A53B	24M FV_EL 2	Inverter	N	4/22/2014	19,232.50
A53B	24M FV_EL 2	Inverter	N	4/24/2014	14,130.00
A53B	Lekkasje på b	Battery	N	5/20/2014	54,865.00
A53B	Lekkasje på b	Battery	N	6/2/2015	291,448.44
A53B	12M FV_EL 2	Inverter	N	6/24/2015	5,130.00
A53B	12M FV_EL 2	Inverter	N	6/25/2015	3,420.00
A53B	24M FV_EL 2	Inverter	N	6/13/2016	0.00
A53B	24M FV_EL 2	Inverter	N	6/16/2016	0.00

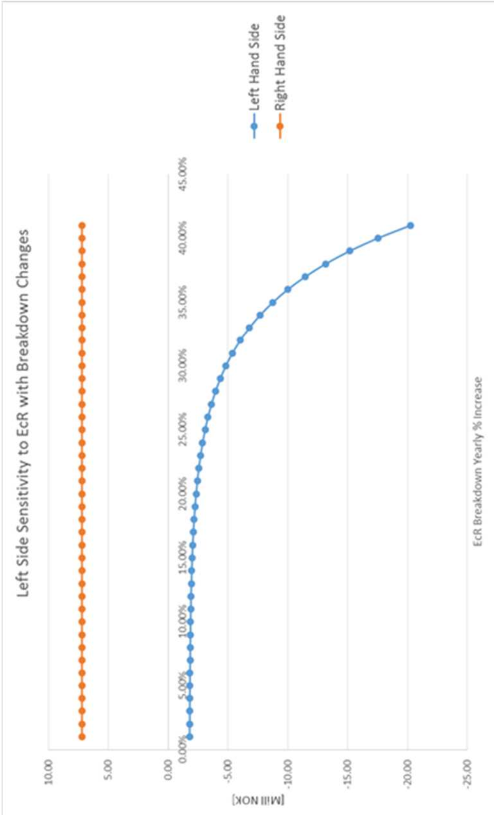
10.12 Appendix L

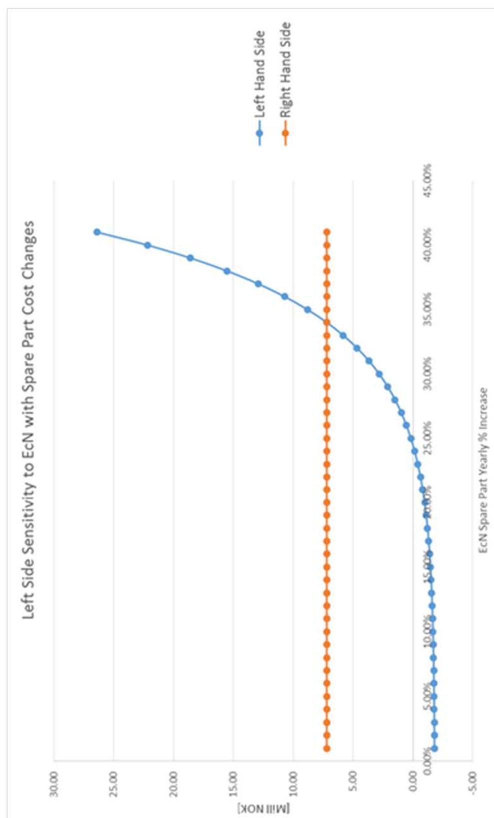


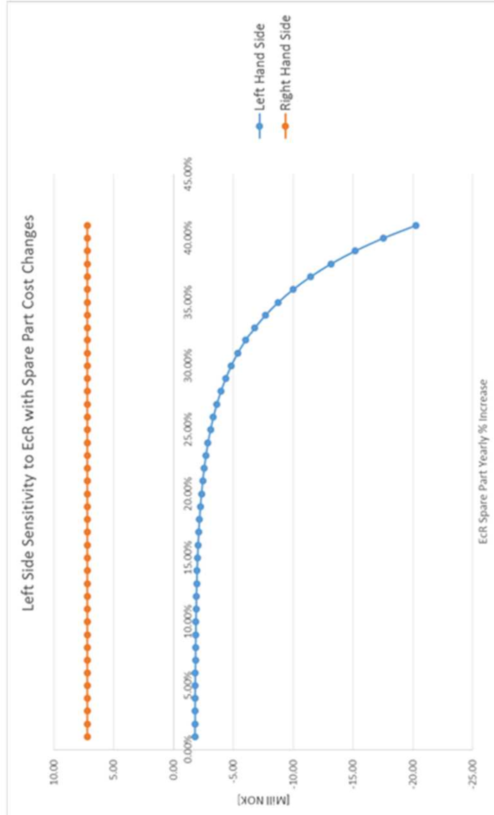


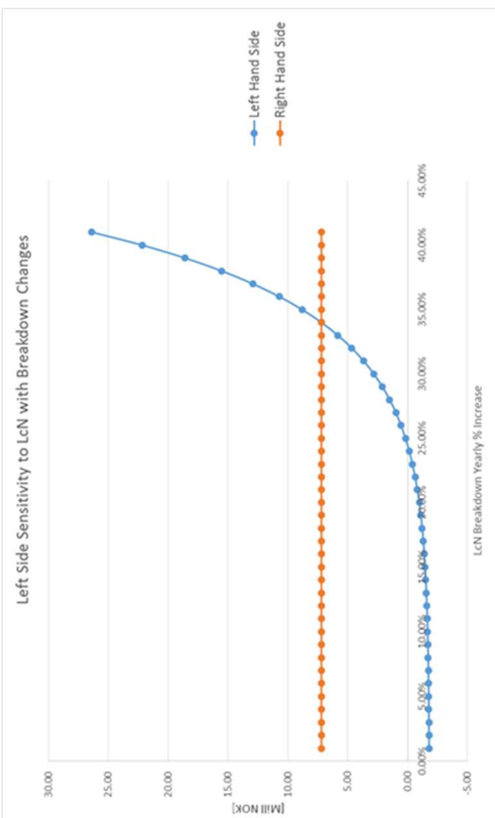


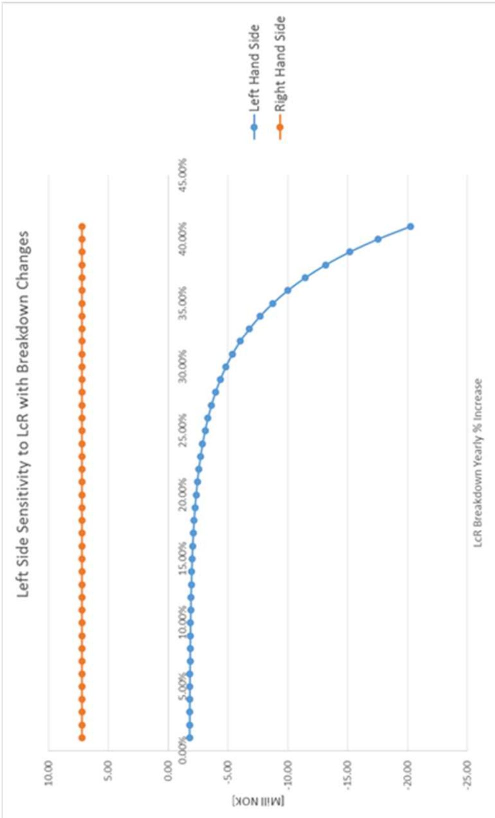

Left Side Sensitivity to EcN with Breakdown Changes
[Mill NOK]
EcN Breakdown Yearly % Increase
Left Hand Side
Right Hand Side

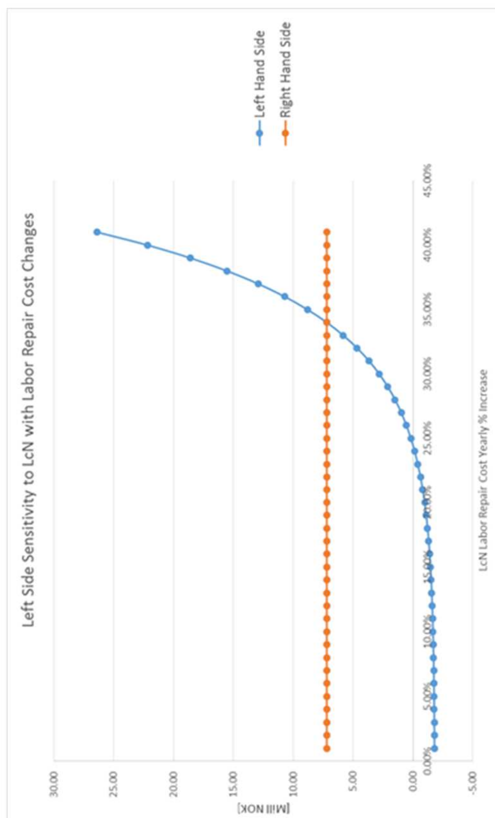

Left Side Sensitivity to EcR with Breakdown Changes
[Mill NOK]
EcR Breakdown Yearly % Increase
Left Hand Side
Right Hand Side

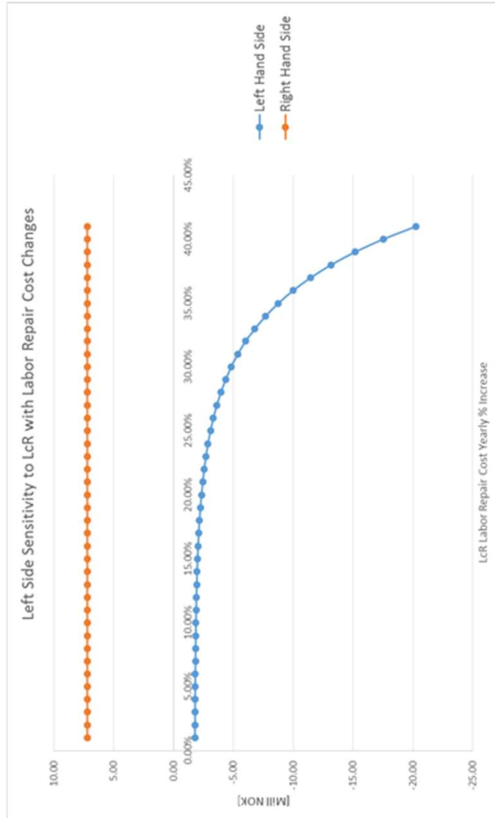

Left Side Sensitivity to EcN with Spare Part Cost Changes
[Mill NOK]
EcN Spare Part Yearly % Increase
Left Hand Side
Right Hand Side

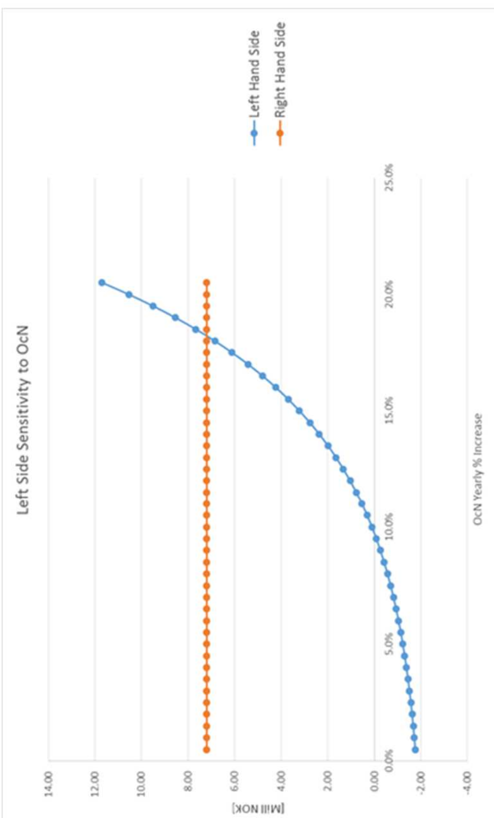

Left Side Sensitivity to EcR with Spare Part Cost Changes
[Mill NOK]
EcR Spare Part Yearly % Increase
Left Hand Side
Right Hand Side

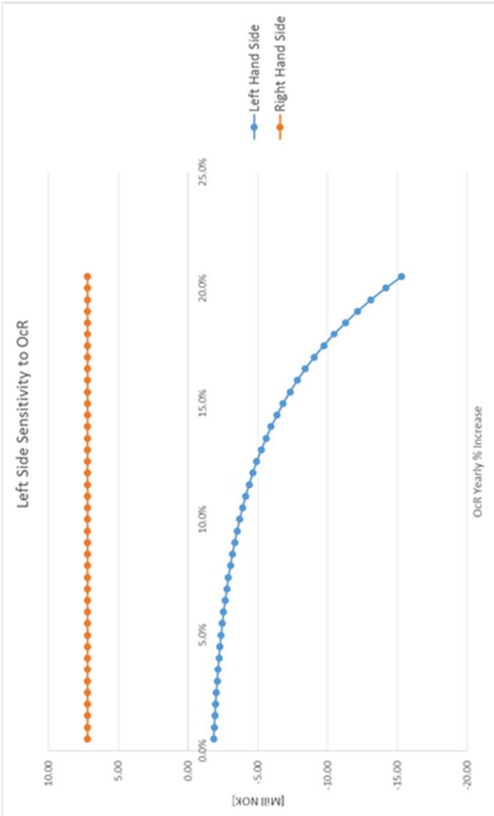

Left Side Sensitivity to LcN with Breakdown Changes
[Mill NOK]
LcN Breakdown Yearly % Increase
Left Hand Side
Right Hand Side

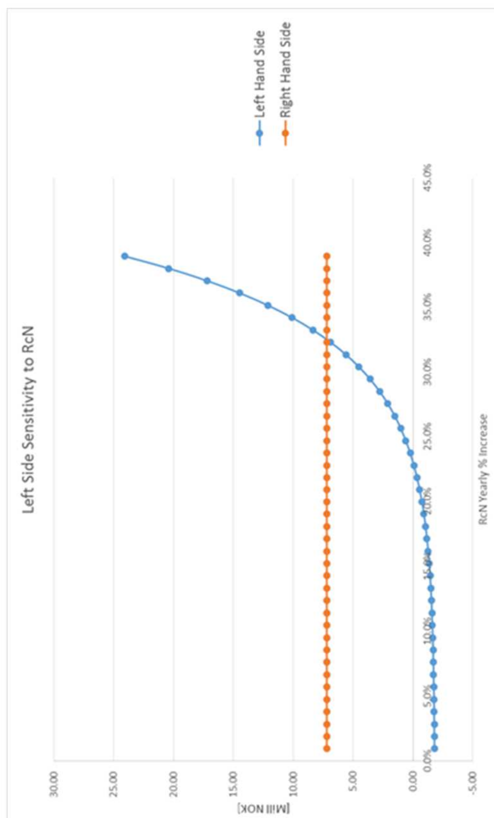

Left Side Sensitivity to LcR with Breakdown Changes
[Mill NOK]
LcR Breakdown Yearly % Increase
Left Hand Side
Right Hand Side

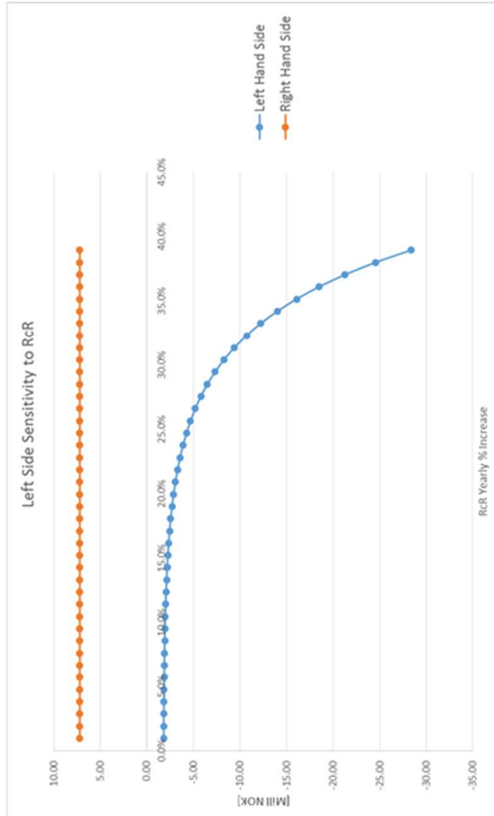

Left Side Sensitivity to LcN with Labor Repair Cost Changes
[Mill NOK]
LcN Labor Repair Cost Yearly % Increase
Left Hand Side
Right Hand Side

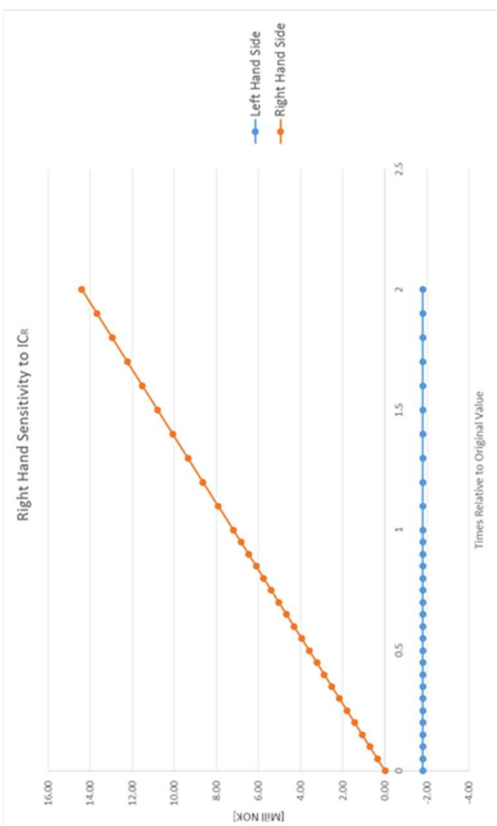

Left Side Sensitivity to LcR with Labor Repair Cost Changes
[Mill NOK]
LcR Labor Repair Cost Yearly % Increase
Left Hand Side
Right Hand Side

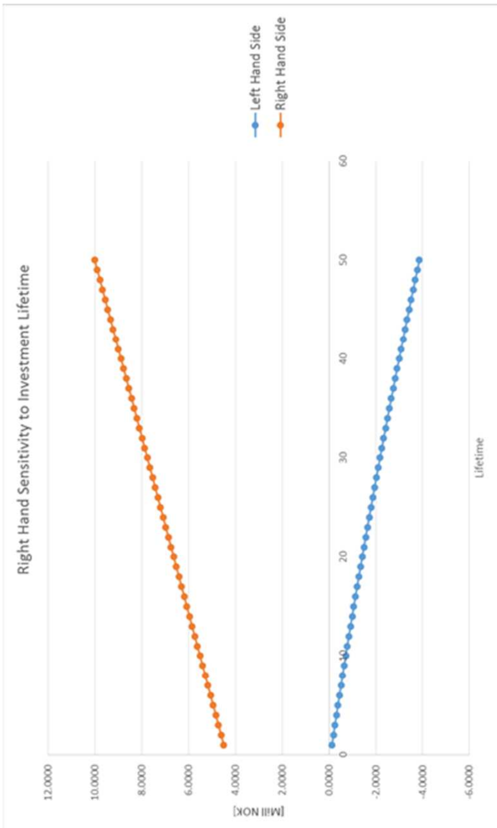

Left Side Sensitivity to OcN
[Mill NOK]
OcN Yearly % Increase
Left Hand Side
Right Hand Side

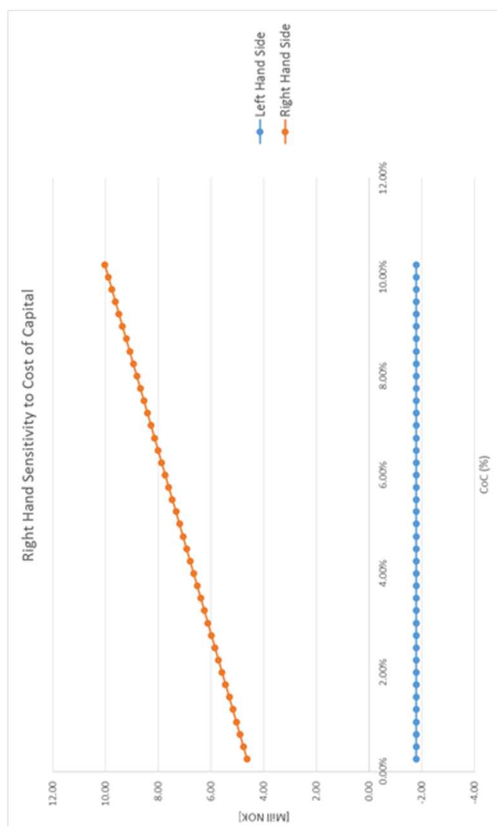

Left Side Sensitivity to OcR
[Mill NOK]
OcR Yearly % Increase
Left Hand Side
Right Hand Side

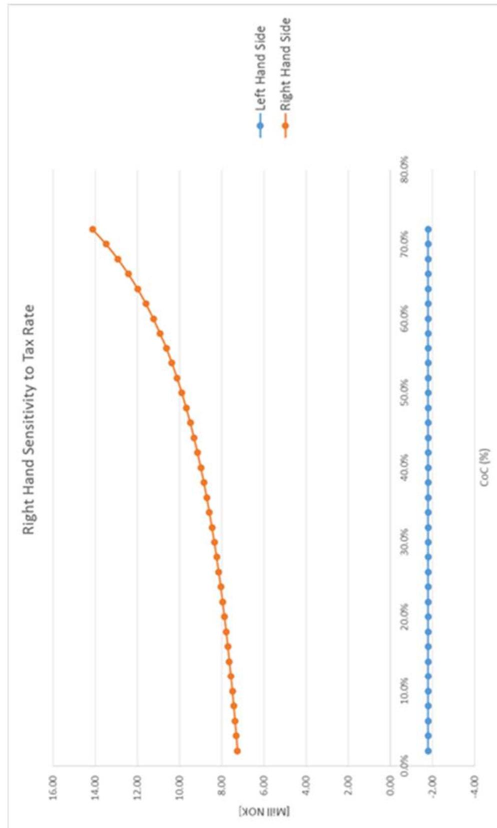

Left Side Sensitivity to RcN
[Mill NOK]
RcN Yearly % Increase
Left Hand Side
Right Hand Side


Left Side Sensitivity to RcR
[Mill NOK]
RcR Yearly % Increase
Left Hand Side
Right Hand Side


Right Hand Sensitivity to ICR
[Mill NOK]
Times Relative to Original Value
Left Hand Side
Right Hand Side


Right Hand Sensitivity to Investment Lifetime
[Mill NOK]
Lifetime
Left Hand Side
Right Hand Side


Right Hand Sensitivity to Cost of Capital
[Mill NOK]
CoC (%)
Left Hand Side
Right Hand Side


Right Hand Sensitivity to Tax Rate
[Mill NOK]
CoC (%)
Left Hand Side
Right Hand Side